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Coastal and Hydraulic Laboratory

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Great Lakes Coastal Flood Study, 2012 Federal Inter-Agency Initiative

Wave Height and Water Level Variability on Lakes Michigan and St Clair

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Final report

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Abstract

The Great Lakes are subject to coastal flooding as a result of severe storms. Strong winds blowing across the surface of the lakes produce high waves and surge. Variations in lake levels due to decadal scale variations in precipitation and anthropogenic activities affect the risk of flooding. In this report, historical storm climatology on Lakes Michigan and St Clair, and the resulting measured waves and water levels, are analyzed in detail. The physical processes that produce coastal flooding are investigated. The detailed history of water level and wave time series and associated probabilities are calculated, with long term, seasonal, and event time scales analyzed separately. Various parametric correlations between time scales and between spatial locations are quantified. A flood map methodology is proposed that improves the accuracy of base flood elevation prediction and improves the uncertainty prediction. The methodology takes full advantage of the latest storm wave and water level hydrodynamic modeling capabilities, as well as long term meteorological, ice, wave, and water level measurements.

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Preface

The study summarized in this report was conducted at the request of the Detroit District (LRE), USACE. Mary Weidel was LRE Program Manager and Greg Mausolf was the primary engineering LRE point of contact. The study was funded by the Federal Emergency Management Agency (FEMA) through LRE and conducted at the Engineering Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL), Vicksburg, MS, during the period Nov 2009 – Apr 2012. The FEMA Lead was Ken Hinterlong, Chief, Risk Analysis Branch, Mitigation Division, FEMA Region V. Julie Tochor, Accenture, was the Program Management Lead for FEMA Region V.

This report was prepared by Dr. Jeffrey A. Melby, Dr. Norberto C. Nadal-Caraballo, and Yamiretsy Pagán-Albelo, Harbors, Entrances, and Structures (HES) Branch, CHL, and Bruce Ebersole, Chief, retired, Flood and Storm Protection Division. In addition, Dr. Kenneth Mitchell, Elizabeth Burg and Laurin Yates assisted in acquiring data and preparing storm summaries for individual storms. Drs. Melby and Nadal-Caraballo, Pagán-Albelo, Yates, and Burg were under the general supervision of Dr. Jackie Pettway, Chief, HES Branch, and Dr. Rose Kress, Chief, Navigation Division. Dr. Mitchell was under the general supervision of Jeffrey Waters, Chief, Coastal Engineering Branch. Dr. William D. Martin was Director, CHL, and Jose Sanchez was Deputy Director, CHL. COL Kevin J. Wilson was Commander and Executive Director of ERDC. Dr. Jeffery Holland was ERDC Director.

Unit Conversion Factors

A sponsor requirement for this study was the use of English Customary units of measurement. Most measurements and calculations were done in SI units and then converted to English Customary. The following table can be used to convert back to SI units.

Multiply	By	To Obtain
Feet	0.3048	meters
cubic feet	0.02831685	cubic meters
pounds (force)	4.448222	newtons
square feet	0.09290304	square meters

1 Introduction

1.1 Overview

Coastal flooding is primarily caused by storm surge and waves but includes many other influences. For the Great Lakes shoreline, the flooding is dependent on the local lake levels, which vary as a result of precipitation and evaporation and other natural processes, as well as anthropogenic activities. Ice cover impacts the flood hazard significantly. These phenomena make the analysis of flood hazard for the lakes unique from ocean coastal areas.

The annual risk of flooding has been computed in the past and mapped by FEMA, and FEMA produces detailed guidance on producing these maps (USACE 1988; FEMA 2003; 2009a, b). Flood Insurance Rating Maps (FIRM)[1] are prepared in engineering studies of flood risk called Flood Insurance Studies (FIS). The maps show planview extents of flood inundation for flood events with specific annual exceedance probabilities. FISs have historically utilized the best available technology and data to compute flood risk.

Recent developments in mathematical and computer modeling of storm winds, waves, and storm surge, combined with more extensive measurements, provide an opportunity to significantly improve the accuracy of these flood risk maps. This document provides an extensive evaluation of long-term lake levels, seasonal trends, and storm-induced changes in lake levels on Lakes Michigan and St. Clair. The statistical characteristics of the data are analyzed in the context of computing flood risk. The results are used as the basis for a proposed strategy for revising the flood risk maps for these lakes.

1.2 FEMA FIRM fundamentals

Within FIRM's, Special Flood Hazard Areas (SFHA) are areas that are subject to floods that have a 1-percent chance of being exceeded in a given year. The corresponding elevation of the water surface is termed the base flood elevation (BFE). The average return period for the BFE is 100 yrs.

[1] http://www.fema.gov/hazard/map/firm.shtm

On a map, these areas would be delineated by contour lines that are lines of equal annual exceedance probability, or AEP, of 1 percent. The 500-yr return period flood contour corresponding to AEP of 0.2 percent is also shown on the FIRM. Appendix A provides background discussion of extremal probability concepts.

The 100-year flood is a flood that would occur once in 100 years on average if you had thousands of 100-year histories. However, reliable measurements are typically available for only the last 40 to 60 years. For a 100-year record, or a single 100-year realization, there is a 63-percent chance of the 100-year flood occurring during a period of 60 years. For 40 years of data, there is only a 33-percent chance that the 100-year flood occurred during this period. For a typical 30-year mortgage, there is a 26-percent chance that the 100-year flood will occur during the lifetime of the mortgage.

Flood Insurance Risk Zone Designations indicate the magnitude of flood hazards. The primary zone for coastal areas is Zone V: *SFHA with a 1-percent flooding AEP characterized as coastal areas where velocity hazards from wave action are possible and where base flood elevations have not been determined in detail*. Other coastal zones are Zone VE and V1 – V30: *SFHA with a 1-percent flooding AEP characterized as coastal areas where velocity hazards from wave action are possible where base flood elevations have been determined in detail*. In addition, Zone X represents *areas above the 1-percent-annual-chance flood level. On the FIRM, a shaded X zone area is subject to inundation by the 0.2-percent-annual-chance flood, and an unshaded X zone area is above the 0.2-percent-annual chance flood level*. A FEMA designated floodway is defined as an area that is prone to flooding to the point that it is uninsurable.

The DFIRM is a digital version of a FIRM to be used in conjunction with Geographic Information Systems (GIS). Digital data from the actual engineering studies can be provided along with the maps.

1.3 Great Lakes overview

The great lakes consist of a system of lakes and connecting waterways. An excellent overview with references is contained in the various FEMA mapping guideline documents in the references section (USACE 1988; FEMA 2003, 2009a, b). The lakes vary in elevation from Lake Superior, at 601 ft above sea level, down to Lake Ontario, at 243 ft (Figure 1). Lake Superior and Lake Huron are connected by the St. Marys River. Lake Huron

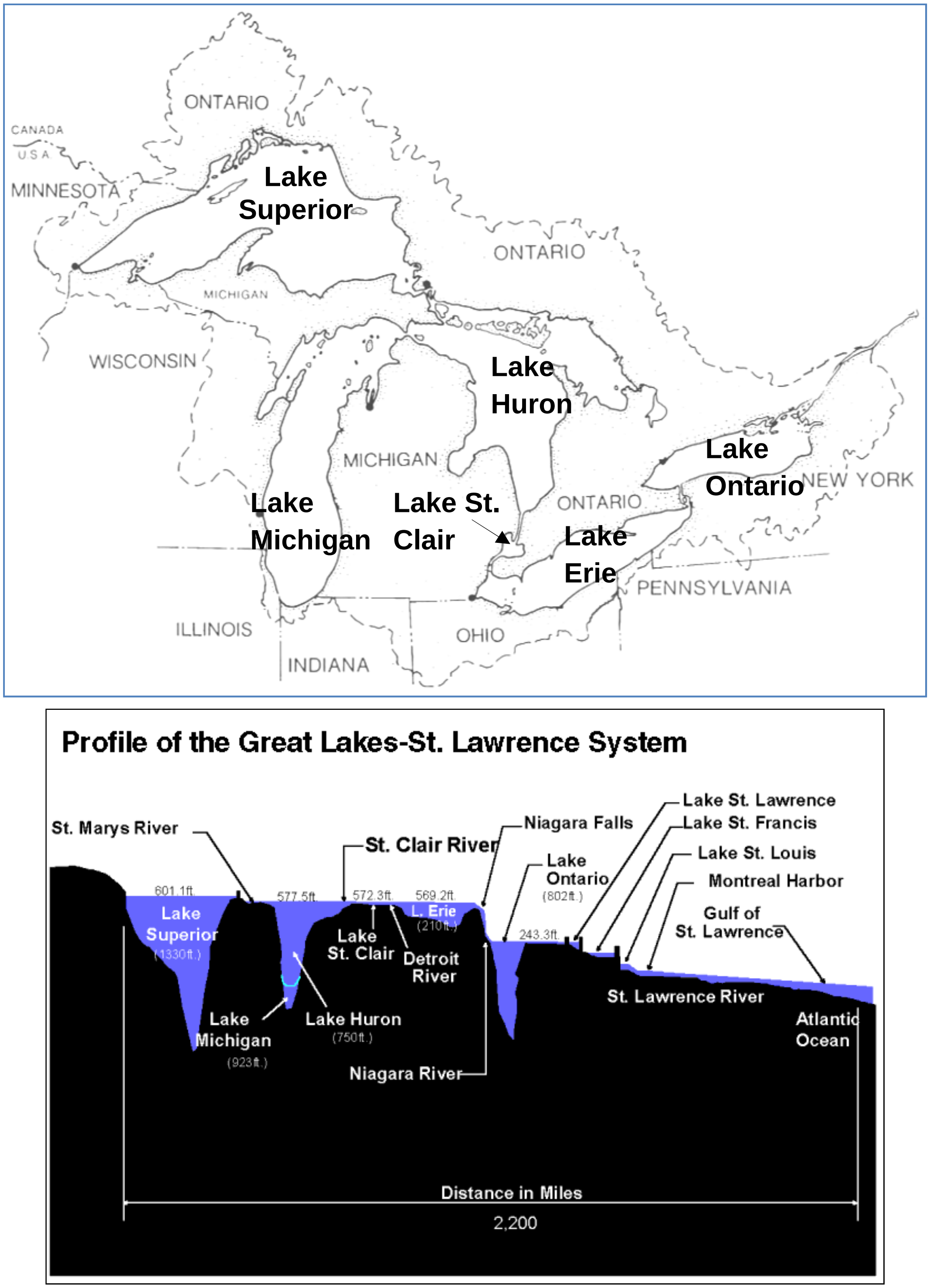

Figure 1. Great Lakes system planview and profile from USACE Detroit District.

and Lake Michigan are connected through the Straits of Mackinac and are essentially at the same elevation. Water flows from Michigan-Huron to Lake St. Clair through the St. Clair River. Lake St. Clair and Lake Erie are connected by the Detroit River. Lake Erie is connected to Lake Ontario by

the Niagara River and Welland Canal. Lake Erie outlets to the Atlantic Ocean through the St. Lawrence River. Levels of lakes Superior and Ontario are regulated by control structures while the connecting waterways of lakes Michigan-Huron and Erie are indirectly controlled. International boards control flow through the control structures to maintain the lakes at optimal levels to balance commerce, recreation, quality of life, and environmental quality and sustainability.

1.4 Lake Michigan-Huron water levels overview

The lake Michigan-Huron system is the largest body of fresh water in the world, by surface area. Lake Michigan long axis is oriented north-south, is about 300 miles long, 50 – 80 miles wide over much of the length, and has an average depth of roughly 300 ft along the long axis. The deepest depth in the lake is 923 ft. The Milwaukee reef divides Lake Michigan into southern and northern pools, both of which circulate clockwise. Lake levels are lowest in the winter and highest in the summer. The lake freezes around the edges but it is unusual for the lake to freeze across. Green Bay is a narrow bay on the western side of Lake Michigan with long axis trending SW-NE. Green Bay is 100 miles long with an average depth of about 35 ft. The bay is roughly 10 miles wide near the city of Green Bay at the southern tip and widens to 20 miles at the connection with Lake Michigan. The bay often freezes over.

The Great Lakes region was covered in glaciers roughly 10,000 years ago and the lake complex formed as a result of advance and retreat of the glaciers as well as glacier melting. The entire area is rising and tilting as a result of post-glacial isostatic rebound. Petty et al. (1996) noted that the average isostatic rebound rate in the northern Lake Michigan region is 0.87 ft/100 yr. They noted that this rate is roughly constant over the last 5000 years. Datums used as reference for NOAA water level measurements are adjusted to account for these types of changes in ground level.

As summarized in USACE (1988), and FEMA (2003, 2009b), lake levels vary as a result of annual and decadal evaporation and rainfall cycles as well as flow into and out of each lake from neighboring lakes. The latter forcing of lake levels is partially influenced by anthropogenic activities. Coastal flooding is primarily the result of storm-induced surge and waves and is directly related to the long-term lake levels. The lake levels vary on annual and decadal scales so there are three basic time scales that are analyzed in this report: long term, seasonal, and event. Tidal forcing of

water levels in the Great Lakes produces only 1-2 inches of variation and is not significant in the context of extremes.

1.5 Lake St. Clair water levels overview

Lake St. Clair is located in the center of the Great Lakes, between the Province of Ontario and the State of Michigan. It is approximately 26 miles long and 24 miles wide, with a surface area of 430 square miles. The maximum natural depth of the lake is 21 ft and the average depth is about 11 ft. A dredged 27 ft navigation channel bisects the lake, running in a northeast-southwest direction between the St. Clair Cutoff in the St. Clair River delta and the head of the Detroit River. Wind forces, along with the flow-through pattern from the St. Clair River, determine the lake's circulation pattern. In general, the water moves in the direction from the St. Clair River to the Detroit River. The lake drains about 4,800 square miles of land drainage area with three major tributaries: the Clinton River in Michigan, and the Sydenham and Thames Rivers in Ontario. However, the St. Clair River provides the vast majority of water supplied to the lake. Two distinct areas of Lake St. Clair are the main body of the lake, laying south and west of the St. Clair River delta, and the northern Anchor Bay area (Derecki 1984).

Ice conditions in Lake St. Clair react quickly to wind and temperature changes. Because it is relatively shallow, the lake has a limited capacity to store heat; consequently, its ice cover forms and melts quickly. The lake usually becomes ice covered by the end of January. During the period of greatest ice cover, the ice is usually fast and thick in the bays and protected areas, with heavy consolidated ice floes of brash and cake ice in the middle of the lake. The stability of the ice cover in the lake is very sensitive to wind forces. The area of Lake St. Clair at the head of the Detroit River is usually ice free because an ice bridge forms above the river head; however, this lake area fills with drift ice following storm breakup of the ice bridge. As the ice begins to melt, the breakup of the lake ice cover occurs quickly. Winds and currents move the drifting ice to the entrance of the Detroit River, where relatively strong river currents move it downstream. The lake is usually free of ice in March (Derecki 1984). Ice cover is tracked by the Great Lakes Environmental Research Laboratory (GLERL) and daily, monthly, and annual data are available.

1.6 Huron-Erie Corridor

Being the smallest of the lakes, Lake St. Clair is not prominent in the Great Lakes System. However, its location is a key connection between the upper and lower Great Lakes. The Huron-Erie Corridor (HEC) serves as a major waterway in the Great Lakes and is the connecting channel between Lakes Huron and Erie. The system consists of the St. Clair River, Lake St. Clair, and the Detroit River, and serves as a recreational waterway, source of drinking water for Detroit and surrounding cities, as well as the only shipping channel to Lakes Huron, Michigan, and Superior (Anderson et al. 2010; Anderson and Schwab, 2011). The HEC stretches over 90 miles from Lake Huron to Lake Erie, and has a surface area of 480 square miles. The driving hydrodynamic forces associated with the HEC differ from those of the Great Lakes as the rivers form a major component of the system (Schwab and Bedford 1994). The dynamics in the HEC are hydraulically driven by the water levels at both Lake Huron and Lake Erie, as well as being driven by the storm-induced lake level variation on Lake St. Clair. In addition, the inflow from tributaries connected to the system can have a noticeable effect on downstream water levels and consequently the hydrodynamics (Anderson et al. 2010).

Lake St Clair and Lake Huron have a difference in water level of about 5 ft. The St. Clair River separates the two lakes. A description of the history of the St Clair River is found on the USACE Detroit District web site. The natural depth of the river channel is about 20 ft. The river was heavily dredged by commercial sand and gravel interests during the early 1900s. This practice was prohibited in 1925. The navigation channel was dredged to 25 ft in the mid-1930s and then to 27 ft in the early 1960s to improve navigation. This latest channel modification improved both the hydraulic efficiency and ice passage efficiency but produced an estimated 1-ft drop in Michigan-Huron lake levels. Recent studies have analyzed continued erosion of the St. Clair River and the possible impact on lake levels.

1.7 Great Lakes water level management

The International Joint Commission (IJC) regulates lake levels (International Joint Commission Levels Reference Study 1993). The legal support for this commission is in the Boundary Waters Treaty of 1909 and in Great Lakes Water Quality Agreement of 1978 (amended 1987). The IJC controls all lake levels through control structures in connecting waterways. In addition, the Michigan-Huron system water levels are influenced by

anthropogenic activities related to water diversion at Chicago and by channel management activities of the St. Clair river channel. The IJC reviews studies related to these activities and makes recommendations to maintain optimal lake levels.

Changnon and Glantz (1996) summarized the history of water diversion in Chicago and its implications on lake levels. They noted that epidemics during the period 1855-1890 were the result of Chicago using lake water to dilute sewage that was returned to the lake via the Chicago River. Chicago built diversion control works during 1894-1899 to reverse the flow of the Chicago River to drain the diluted pollution down to the Illinois River. This diversion of lake water has caused controversies ever since. The diversion increased to a maximum of 10,500 cfs in the late 1920s. Following a U.S. Supreme Court ruling in 1930 regulating the diversion, the amount of diversion was decreased rapidly to a relatively constant level of 3000 cfs beginning in 1939 and extending through the 1990s with small variations as a result of natural lake level variability. The USACE Detroit District web site contains a summary on the diversion and related activities along the Calumet River.

1.8 Great Lakes storms

For the Great Lakes, coastal flooding is primarily caused by a combination of storm surge and wave inundation, both of which are primarily generated by high winds blowing across the lake. High winds blowing in a specific direction can develop significant shear stress on the water surface producing large waves. The shear stresses, combined with pressure differentials, can cause water to pile up on the shoreline. This is known as storm surge. The two primary categories of surge-causing storm events are: (1) cold-season non-convective wind events (NCWE) from extra-tropical cyclones, and (2) warm-season frontal systems producing thunderstorm-related wind events (e.g. Knox et al. 2008, Lacke et al. 2007). NCWEs are defined as A: sustained winds of at least 40 mph for at least 1 hr or B: gusts of at least 58 mph (Lacke et al. 2007, Niziol and Paone 1991). These criteria can be compared to the tropical storm definition of minimum sustained wind speeds of 38 mph and severe weather criteria gusts of 58 mph. The NCWEs are normally a result of winter storms (November – April) that emanate from the Rocky Mountains and pass through the Great Lakes region from the SW to the NE. A small number of storms originate from the Canadian Rockies and stay north of the lakes. The degree of flooding from these events depends on lake level, ice cover, and storm-induced wave and

water level nearshore conditions. These, in turn, can depend on many things including the details of the climatology, lake seiching, rainfall runoff, snow-melt runoff, and other nearshore effects.

If surge occurs on a given shoreline, then a setdown or lowered water level will occur on the opposite side of the lake. For example, if storm surge occurs along the southern shore of Lake Michigan, then the northern lakeshore is likely to have a coincident lowered water level. Typically, the lake will oscillate as a result of this instability and the oscillation will damp out fairly quickly. This oscillation is called seiching. A seiche is a standing wave which has been formed in an enclosed or semi-enclosed body of water. Seiche is typically not of particular concern for extreme water levels because it is less than the initiating surge and is not accompanied by the large waves that are coincident with the surge.

Ice cover is prevalent on the Great Lakes in winter months. Ice cover is tracked by the NOAA Great Lakes Environmental Research Laboratory (GLERL) and daily, monthly, and annual data are available. Lake ice forms from the shore out but is often not solid. Lake Michigan seldom freezes over but Green Bay often freezes over. Solid ice will prevent wind stress on the water surface and will damp surges. However, chunk ice can increase the drag coefficient on the water and exacerbate shear stress and therefore waves and surge. This is described more fully in the companion reports on surge and wave modeling (Jensen et al. 2012).

1.9 Existing FEMA mapping guidelines

BFEs are set at the crest of the wave in the FEMA Guidelines. The maximum breaking wave crest elevation is built on the 100-year return-period still-water depth which is the difference between the 100-year return period stillwater elevation and the ground elevation. The 100-year stillwater depth is computed from historical measurements. The ground elevation is computed with erosion expected to occur during the 100-year flood event. The breaking wave height is prescribed as $H_b = 0.78d_{100}$ and the maximum breaking wave crest height above the stillwater elevation as $0.55d_{100}$. So the total BFE is the sum of the ground elevation relative to the datum plus the 100-year stillwater depth, d_{100}, plus the breaking wave crest height, $0.55d_{100}$. For an area with steeply sloping shoreline or structure, where wave runup can exceed the height of the maximum wave, then the maximum wave runup height is summed with the stillwater elevation.

For the 2003 map Guidelines (FEMA 2003), the process was defined as follows:

1. Determine annual maximum water level from existing gage records. Interpolate between neighboring gages.
2. For each year for which data are available, scan through the record and select several coincident elevated storm water level and wave height pairs that are expected to produce the largest wave runup at the shoreline.
3. Find the largest runup elevations for each year and fit a suitable probability distribution to the annual maxima using curve fitting methods such as the maximum likelihood method and the method of linear-moments to determine the χ-percent-annual-chance flood elevation.
4. Add the appropriate long-term lake water level lake-specific adjustment factor based on the return period flood elevation of interest.

In the 2009 Great Lakes Coastal Guidelines Update[1] (FEMA 2009a, b), a response-based methodology is proposed as follows:

1. Water level and wave date pairs:
   Three different wave/water level data pairs that are expected to produce the highest runup are extracted from the hourly water level measurements and Wave Information Study (WIS) hindcasts (http://chl.erdc.usace.army.mil/wis), and these 3 conditions are analyzed to determine which results in the maximum flood hazard:
   a. Data Pair #1 – Annual maximum water level and coincident wave height;
   b. Data Pair #2 – Maximum storm wave height and coincident water level, within 24 hours of annual maximum water level;
   c. Data Pair #3 – Annual maximum wave height and coincident water level.
2. Runup dominated shorelines:
   a. Perform a statistical analysis of long term lake level variations and produce a probability distribution of long term water levels;
   b. Perform a statistical analysis of storm-induced flood hazard elevation (surge + wave runup) and produce a probability distribution of flood hazard elevation at the shoreline. This analysis is conducted on the mean lake level;

[1] https://www.floodmaps.fema.gov/#lakes

   c. Total flood hazard is determined through the convolution of the distributions of both the long term and event scale components of flooding;
   d. An adjustment factor is computed as the difference between: (1) the 1-percent-annual-chance flood elevations, determined from flood elevation from the full convolution, and (2) the 1-percent-annual-chance flood elevations, determined based solely on the long term average lake level;
   e. The final BFE is determined as the sum of 1-percent exceedance lake level and the adjustment factor.
3. Overland wave propagation: Use the 1-percent-annual-chance water level and a wave height associated with this flooding condition.

1.1 Discussion

For all locations around the lake, the actual 1-percent AEP water level is unknown and must be determined. The computation of the BFE must consider the maximum water levels and must include all contributing factors including background lake level, seasonal variability and event driven water level. The dominant event contributors might include storm surge, wave runup, and wave setup, as well as local runoff or ice melt. The interactions between all contributing parameters are complex and highly nonlinear. Winds blowing across the lake surface dominate the forcing of storm surge and waves, and these wind fields vary in both time and space. Atmospheric pressure contributions are significant. High and low pressure centers can exist simultaneously over the lakes exacerbating the pressure contribution to storm surge and seiche. Local meteorology, ice cover and storm duration impact the surge and waves. Both non-convective and convective events can be fast moving and the peaks may not be captured in measurements. Storms commonly interact in the region to produce strong winds on the lake in a sometimes unpredictable way. Storm surge is impacted by shallow water marshes that can absorb surge energy. These marsh areas may or may not be flooded, depending on the lake level, and they may be covered in ice, so their impact varies considerably. Nearshore wave transformation on a barred-beach profile impacts the profile and this complex mechanism depends on the lake level. All of these and other minor impacts and contributions to water levels combine in a complex nonlinear manner that varies around the lake perimeter.

The existing Guidelines consider the above listed contributors in a reasonable manner if one is limited to measured water level data. However,

there are a few significant weaknesses in the existing methodology that could be improved. Mean and maximum monthly water level gage measurements exist for record lengths of roughly 100 years for several sites around the lake. Continuous hourly water level measurements dating from 1970 exist for only nine point locations around Lake Michigan and Green Bay. As will be shown in the following analysis, there is little correlation in storm water levels between gage sites. That is, storms with the highest storm surge at one site are different from the highest ranking storms at a neighboring site. So interpolating between gage locations using measured water level data does not have any physical justification. Interpolation of widely-spaced and uncorrelated gage measurements will produce large and unknown errors. The longer records that are presently available provide a significant reduction in statistical uncertainty over those that were available in the mid-1980s. However, the high-quality hourly measurements are only available since 1970. To compute a 100 year return period water level, these relatively short records must be extrapolated in time by a factor of more than two. When combined with the interpolation errors, the resulting BFE prediction will include large errors. Finally, empirical wave runup models based on limited laboratory data are typically used for BFE calculation. These models are not very accurate for varying nearshore bathymetry (Melby 2012).

The 2009 Guidelines update recommends computing annual exceedance water levels on mean lake levels and then applying a convolution-determined adjustment factor to account for the long term variability of the lake. Convolution of event scale and long term water level distributions is reasonable from a statistical point of view because these two scales are mostly independent. However, the complex and nonlinear physical interactions between long term lake level and nearshore surge and waves are ignored in this process. Convolution assumes a relatively linear relationship between lake level and event scale processes. Changing long term water levels impacts the width of the surf zone, and the shape of the barred profile as well as the location of the dune and other shoreline features. Further, the method assumes lake levels are normally distributed and makes related broad simplifications without analytical support. Without more sophisticated analysis, the uncertainty introduced in this method is unknown and likely to be large. The errors quoted in the Guideline update do not account for this uncertainty. It is expected that these errors can be large and should be reduced by using the methods

outlined herein. However, in future pilot studies it may be found that the simpler method is reasonably accurate.

An improvement in accuracy can be obtained by utilizing modern numerical hydrodynamic models to predict waves and surges with high spatial resolution along the coast. Modern planetary boundary layer models along with quality wind measurements provide improved wind and pressure fields for driving surge and wave models. High-fidelity surge and short wave models, such as ADCIRC, STWAVE, and CMS-Wave, are routinely used in regional coastal studies. Numerical models that compute detailed nearshore wave transformation with wave breaking, wave runup, and wave overtopping, such as BOUSS-1D, BOUSS-2D, and CSHORE, have also become fairly standard in coastal engineering in the last decade. It has become common to model each significant storm in studies of extreme storm inundation. When combined with high-fidelity long-term wave, water level and meteorological measurements, significant improvements in BFE calculation accuracy can be attained compared to previous FIS studies.

The overall goal of this study was to provide a method for making BFE predictions as accurate as possible given the present state of technology and knowledge of the physical processes. The detailed analytical and statistical analyses of measured data summarized in this report have improved our understanding of the processes and the impacts on the BFE's and so will improve the accuracy and the quantification of uncertainties. The analysis within this report combined with the recommended mapping methodology summarized herein and elucidated in Nadal et al. (2012) is intended to reduce the errors inherent in the existing BFE prediction methods and provide methods to quantify the uncertainty.

2 Data Summary

2.1 Datum

All water levels are referenced to the most recent datum, IGLD85. A description of the datum can be found on the USACE Detroit District web site[1]. The low water datums are as listed in Table 1.

Table 1. Elevations of low water datum.

Lake	Low Water Datum Elevation	
	ft Above IGLD85	ft Above NGVD29
Lake Superior	601.1	601
Lake Michigan	577.5	578
Lake Huron	577.5	578
Lake St. Clair	572.3	573
Lake Erie	569.2	570
Lake Ontario	243.3	244

2.2 Water level measurements

Water level measurements were acquired from NOAA for Lake Michigan for 13 stations[2]. Long term data were available from nine of these stations as summarized in Tables 2 - 4. Data collected since 1970 are summarized in Table 3; measurements were collected at 6-min or hourly intervals. The 6-min data are collected from mostly down-looking acoustic gages that sample at 4-Hz. The gages output 1 sec of data for each four samples. The gage samples for 90 sec on either side of the time stamp, reports an average for the 180-sec record and this process is repeated every 6-min. Hourly water levels reported from these gages are the 180-sec record collected on the hour. Pre-1970 data are summarized in Table 4 and are available only as monthly averages and maxima and are sporadic. The station locations are shown in Figures 2 and 3 and the data are analyzed in the following sections.

[1] http://www.lre.usace.army.mil/greatlakes/hh/newsandinformation/iglddatum1985/

[2] http://tidesandcurrents.noaa.gov/station_retrieve.shtml?type=Great+Lakes+Water+Level+Data

Table 2. Coordinates of NOAA water level gages for Lakes Michigan and St Clair.

Station	Lake	Station Number	Latitude	Longitude
Mackinaw City	Michigan	9075080	45° 46.6' N	84° 43.5' W
Ludington, MI	Michigan	9087023	43° 56.8' N	86° 26.5' W
Holland, MI	Michigan	9087031	42° 46.0' N	86° 12.0' W
Calumet Harbor, IL	Michigan	9087044	41° 43.7' N	87° 32.3' W
Milwaukee, WI	Michigan	9087057	43° 0.1' N	87° 53.2' W
Kewaunee, WI	Michigan	9087068	44° 27.8' N	87° 30.0' W
Sturgeon Bay, WI	Michigan	9087072	44° 47.7' N	87° 18.8' W
Green Bay, WI	Michigan	9087079	44° 32.4' N	88° 0.4' W
Port Inland, MI	Michigan	9087096	45° 58.1' N	85° 52.2' W
Algonac, MI	St. Clair	9014070	42° 37.2' N	82° 31.6' W
St Clair Shores, MI	St. Clair	9034052	42° 28.3' N	82° 52.3' W
Fort Wayne, MI	St. Clair	9044036	42° 17.9' N	83° 50.5' W
Windmill Point, MI	St. Clair	9044049	42° 21.4' N	82° 55.8' W

Table 3. Recording periods for measured water level data for Lakes Michigan and St. Clair. Lake Michigan is in upper portion of table and Lake St. Clair the lower.

Station	Station Number	6-Minute Records	Hourly Records
Mackinaw City	9075080	none	1/1970 – 1/2010
Ludington, MI	9087023	1/1998 – 1/2010	1/1970 – 1/2010
Holland, MI	9087031	9/2000 – 1/2010	1/1970 – 1/2010
Calumet Harbor, IL	9087044	1/1996 – 1/2010	1/1970 – 1/2010
Milwaukee, WI	9087057	1/1996 – 1/2010	1/1970 – 1/2010
Kewaunee, WI	9087068	10/2000 – 1/2010	10/1973 – 1/2010
Sturgeon Bay, WI	9087072	8/1999 – 1/2010	1/1970 – 1/2010
Green Bay, WI	9087079	1/1998 – 1/2010	1/1970 – 1/2010
Port Inland, MI	9087096	9/1994 – 1/2010	1/1970 – 1/2010
Algonac, MI	9014070	1/1996 – 2010	1/1975 – 1/2010
St Clair Shores, MI	9034052	1/1996 – 2010	1/1970 – 1/2010
Fort Wayne, MI	9044036	1/1996 – 2010	1/1970 – 1/2010
Windmill Point, MI	9044049	1/1999 – 2010	1/1970 – 1/2010

Table 4. Recording Periods for monthly measured and computed water level data for Lakes Michigan and St Clair. Lake Michigan is in upper portion of table and Lake St. Clair the lower.

Station	Station Number	Recorded Monthly Average	Recorded Monthly Maximum	Computed Monthly Average and Maximum
Mackinaw City, MI	9075080	4/1899 – 1/2007	1/1915 – 12/1989	1/1970 – 1/2010
Ludington, MI	9087023	Part. yr: 11/1895 – 8/1950, Full yr: 8/1950 – 1/2007	8/1950 – 12/1989	1/1970 – 1/2010
Holland, MI	9087031	Part. yr: 6/1894 – 8/1950, Full yr: 5/1959 – 1/2007	5/1959 – 12/1989	1/1970 – 1/2010
Calumet Harbor, IL	9087044	2/1903 – 1/2007	1/1915 – 12/1989	1/1970 – 1/2010
Milwaukee, WI	9087057	1/1860 – 1/2007	1/1915 – 12/1989	1/1970 – 1/2010
Kewaunee, WI	9087068	10/1973 – 1/2007	1/1975 – 12/1989	10/1973 – 1/2010
Sturgeon Bay, WI	9087072	1/1905 – 1/2007	1/1950 – 12/1989	1/1970 – 1/2010
Green Bay, WI	9087079	7/1953 – 1/2007	7/1954 – 12/1989	1/1970 – 1/2010
Green Bay, WI	9087088	None	None	1/1970 – 1/2010
Port Inland, MI	9087096	11/1964 – 1/2007	1/1965 – 12/1984	1/1970 – 1/2010
Algonac, MI	9014070	1901,1926-1929,1947, 1952-1969, 1975-2010	1952-1969, 1975-2010	1/1975 – 1/2010
St Clair Shores, MI	9034052	1968-2010	1968-2010	1/1970 – 1/2010
Fort Wayne, MI	9044036	1970-2010	1970-2010	1/1970 – 1/2010
Windmill Point, MI	9044049	1897-2010	1952-2010	1/1970 – 1/2010

2.3 Other data

Meteorological data acquired from the NOAA National Climatic Data Center (NCDC)[1] are summarized in Table 5.

Wave and over-water meteorological data for Lake Michigan acquired from the NOAA National Data Buoy Center (NDBC)[2] are as follows:

1. NDBC buoy 45002: 9/1979 – 11/2009
2. NDBC buoy 45007: 7/1981 – 11/2009

[1] http://cdo.ncdc.noaa.gov/pls/plclimprod/poemain.accessrouter?datasetabbv=DS3505

[2] http://www.ndbc.noaa.gov/

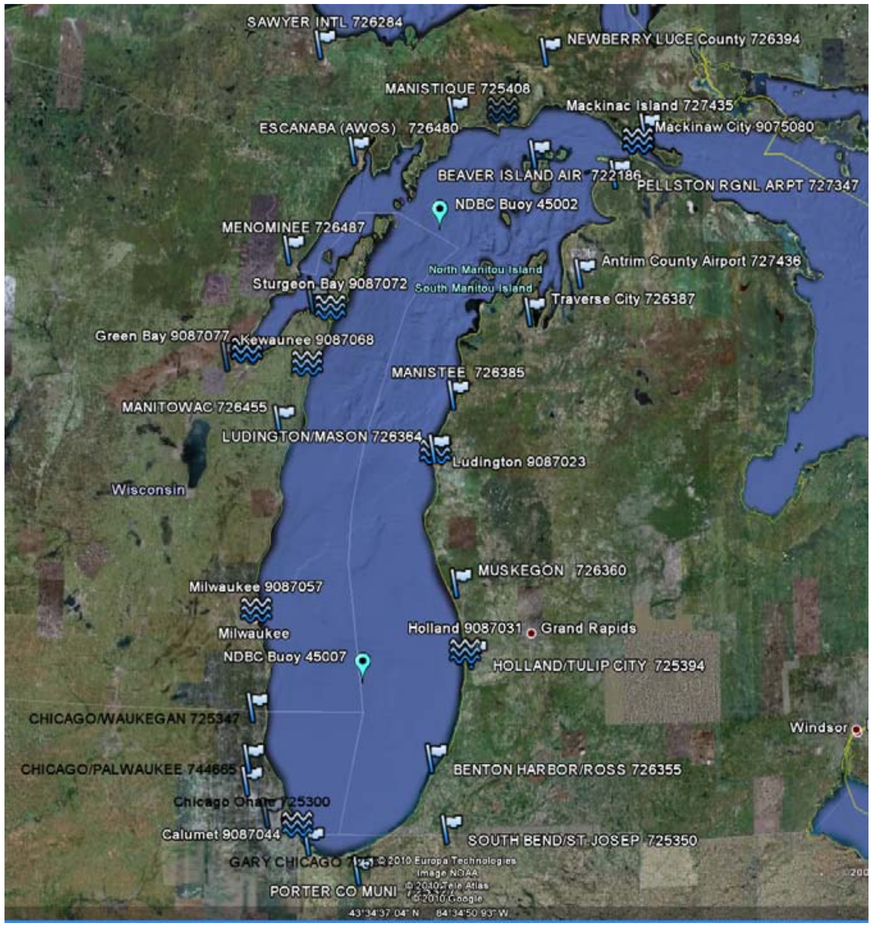

Figure 2. Locations of NOAA water level gages (three wavy lines), wave rider buoys (inverted teardrop) and meteorological (met) stations (flag) on Lake Michigan.

Wave data from Lake St. Clair are analyzed in Jensen et al. (2012).

Wave hindcasts were used herein as surrogates for measured waves in the storm sampling process. Wave Information Study (WIS) hindcasts were available for Lake Michigan for the period from 1956 to 1997. These hindcasts have since been superseded with higher fidelity modeling so the WIS results quoted herein should not be used in future studies.

Ice Data were acquired from the NOAA Great Lakes Environmental Research Laboratory (GLERL) as follows:

1. Daily ice cover maps: 1973 – 2002
2. Daily average times series charts: 1973 – 2002
3. Daily gridded ice cover data: 1973 – 2002
4. GLERL weekly, seasonal, annual statistics in reports: 1898 – 2002

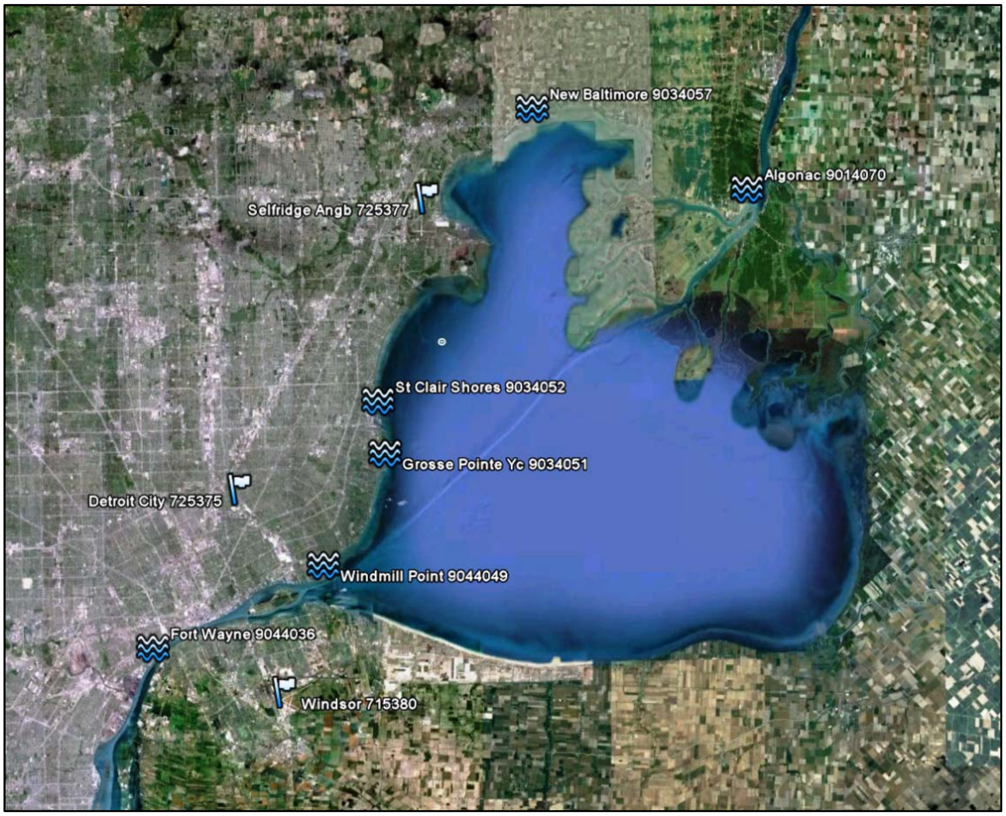

Figure 3. Location of NOAA water level gages (three wavy lines) and meteorological stations (flag) on Lake St. Clair.

Table 5. Recording periods for measured meteorological data. Lake Michigan is in upper portion of table and Lake St. Clair the lower.

Station	Station Number	Latitude	Longitude	Hourly Records
Chicago/O'Hare	725300/94846	41.783˚ N	87.750˚ W	1/1956 – 1/2010
Chicago/Midway	725340/14819	41.986˚ N	87.914˚ W	1/1948 – 1/2010
Traverse City/Cherry	726387/14850	42.947˚ N	87.897˚ W	1/1949 – 1/2010
Milwaukee/Mitchell	726400/14839	44.513˚ N	88.120˚ W	1/1950 – 1/2010
Green Bay/Straubel	726450/14898	44.741˚ N	85.583˚ W	1/1956 – 1/2010
Mackinac Island	727435/54820	45.865˚ N	84.637˚ W	10/1956 – 1/2010
Windsor, CAN	715380/99999	42.267˚ N	82.967˚ W	7/1955 – 1/1963 1/1973 – 1/2010
Detroit Metro	725370/94847	42.215˚ N	83.349˚ W	1/1960 – 1/2010
Detroit City, MI	725375/14822	42.409˚ N	83.010˚ W	7/1930 – 1/1948 1/1966 – 1/2010
Selfridge ANGB, MI	725377/14804	42.613˚ N	82.832˚ W	1/1937 – 1/2010

Ice data are analyzed in Jensen et al. (2012).

Wave hindcast data were acquired from the U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory Wave Information Studies web site[1] for the period 1/1956 – 12/1997.

In addition to the preceding referenced data sources, climate and storm historical data were acquired from the following sources:

1. U.S. Dept. of Agriculture Weekly Weather and Crop Bulletin: http://usda.mannlib.cornell.edu/MannUsda/viewDocumentInfo.do?documentID=1393
2. NOAA National Weather Service: http://www.nws.noaa.gov/
3. University of Wisconsin Satellite Observations: http://www.ssec.wisc.edu/sose/glwx_activity.html
4. NASA Atlas of Extratropical Storm Tracks: http://data.giss.nasa.gov/stormtracks/

[1] http://frf.usace.army.mil/cgi-bin/wis/atl/atl_main.html

3 Coastal Data Characteristics for Lake Michigan

3.1 Long term trends in water levels

As described previously, long-term trends in lake levels in the Great Lakes are a result of both anthropogenic and natural processes. Natural processes include precipitation and evaporation where lake levels drop during periods of dry or cold weather and drought and rise during periods of heavy rainfall and resulting runoff or snowmelt. Decadal forcing, such as El Niño/La Niña cycles, can affect the lakes. Anthropogenic activities that affect water levels include lake level control at lake control structures, water use by municipalities, Chicago River diversion, and St. Clair River dredging. Table 6 lists the mean and variance of long-term lake levels from FEMA (2009a). Long-term variations span about a 6-ft range.

Table 6. Long term average lake levels.

	Lake Superior	Lake Michigan	Lake Huron	Lake Ontario	Lake Erie
Mean (ft, IGLD 1985)	601.59	578.73	578.73	245.19	571.17
Variance	0.22	1.36	1.36	0.24	0.92

3.1.1 Basis of comparison

Adjustment values to account for changes in flow conditions over time due to anthropogenic activities such as major dredging, diversion, or water management regulations were applied to the water level measurements. The Basis of Comparison (BOC) corrections were from the International Joint Commission (IJC) Levels Reference Study (1993). These values, shown in Table 7, were applied to the water level records herein. Only the adjusted water level values were analyzed in this study. At the time of the initial analysis, new adjustments (IJC 2003) (Table 8) were under review but not available. Although the plots and data described in this report utilized the old adjustments, many of the analyses were redone with the new BOC adjustments. The conclusion was that the BOC revision did not affect the general characteristics of the data nor did it affect any conclusions described herein so the analysis based on the older adjustments was retained.

Table 7. Basis of comparison Lakes Michigan and Huron water level corrections in ft from 1993.

Table 2.2
Basis of Comparison (BOC) Corrections in feet
for Lakes Michigan and Huron
1915 through 1989

Year	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1915	0.12	0.11	0.11	0.12	0.13	0.14	0.14	0.14	0.14	0.16	0.17	0.2
1916	0.22	0.25	0.29	0.32	0.35	0.37	0.37	0.37	0.35	0.34	0.31	0.28
1917	0.26	0.24	0.22	0.19	0.17	0.14	0.1	0.07	0.04	0	-0.04	-0.06
1918	-0.06	-0.06	-0.04	-0.03	-0.02	-0.02	-0.02	-0.03	-0.04	-0.04	-0.04	-0.01
1919	0.03	0.07	0.13	0.18	0.23	0.26	0.28	0.29	0.28	0.27	0.26	0.25
1920	0.26	0.27	0.27	0.27	0.27	0.26	0.24	0.23	0.23	0.22	0.21	0.21
1921	0.21	0.22	0.25	0.28	0.31	0.34	0.36	0.37	0.38	0.37	0.36	0.36
1922	0.36	0.37	0.38	0.38	0.38	0.39	0.39	0.39	0.39	0.39	0.39	0.39
1923	0.39	0.38	0.37	0.35	0.34	0.33	0.33	0.32	0.31	0.3	0.29	0.27
1924	0.26	0.25	0.26	0.26	0.27	0.27	0.27	0.28	0.29	0.31	0.32	0.33
1925	0.32	0.31	0.29	0.27	0.25	0.23	0.2	0.17	0.13	0.1	0.06	0.04
1926	0.02	0	0	-0.01	0	0.01	0.03	0.06	0.1	0.13	0.17	0.19
1927	0.21	0.22	0.22	0.22	0.22	0.24	0.27	0.31	0.36	0.41	0.45	0.47
1928	0.48	0.49	0.49	0.49	0.49	0.48	0.48	0.47	0.46	0.45	0.45	0.44
1929	0.44	0.44	0.44	0.42	0.41	0.39	0.37	0.35	0.33	0.31	0.31	0.31
1930	0.31	0.32	0.33	0.35	0.37	0.38	0.37	0.37	0.37	0.37	0.39	0.4
1931	0.42	0.43	0.45	0.47	0.5	0.53	0.55	0.58	0.6	0.61	0.61	0.61
1932	0.61	0.61	0.61	0.62	0.63	0.64	0.65	0.66	0.67	0.68	0.69	0.7
1933	0.72	0.72	0.73	0.73	0.72	0.72	0.71	0.71	0.7	0.68	0.67	0.65
1934	0.64	0.64	0.64	0.64	0.64	0.63	0.61	0.59	0.57	0.57	0.56	0.56
1935	0.56	0.56	0.55	0.54	0.52	0.49	0.46	0.43	0.4	0.38	0.36	0.35
1936	0.36	0.37	0.38	0.39	0.4	0.4	0.4	0.4	0.38	0.35	0.33	0.32
1937	0.31	0.31	0.31	0.32	0.33	0.35	0.38	0.4	0.43	0.46	0.5	0.53
1938	0.56	0.57	0.57	0.56	0.52	0.48	0.43	0.38	0.34	0.3	0.28	0.27
1939	0.27	0.27	0.28	0.27	0.26	0.23	0.2	0.18	0.15	0.13	0.12	0.12
1940	0.12	0.14	0.16	0.19	0.22	0.26	0.27	0.27	0.27	0.25	0.23	0.21
1941	0.18	0.16	0.14	0.14	0.15	0.17	0.19	0.21	0.22	0.24	0.25	0.26
1942	0.27	0.27	0.27	0.26	0.25	0.23	0.2	0.18	0.16	0.16	0.18	0.2
1943	0.22	0.23	0.23	0.22	0.18	0.12	0.05	-0.02	-0.09	-0.15	-0.19	-0.21
1944	-0.2	-0.18	-0.17	-0.16	-0.18	-0.21	-0.25	-0.28	-0.26	-0.22	-0.18	-0.15
1945	-0.13	-0.11	-0.11	-0.12	-0.13	-0.14	-0.14	-0.14	-0.13	-0.13	-0.14	-0.15
1946	-0.17	-0.18	-0.18	-0.18	-0.16	-0.15	-0.13	-0.12	-0.11	-0.1	-0.1	-0.09
1947	-0.09	-0.09	-0.08	-0.07	-0.07	-0.08	-0.11	-0.15	-0.19	-0.23	-0.27	-0.31
1948	-0.33	-0.34	-0.35	-0.34	-0.34	-0.32	-0.31	-0.28	-0.26	-0.23	-0.2	-0.17
1949	-0.15	-0.14	-0.13	-0.12	-0.11	-0.09	-0.06	-0.04	-0.01	0.02	0.06	0.09
1950	0.12	0.14	0.16	0.17	0.17	0.15	0.13	0.09	0.06	0.02	0	-0.03
1951	-0.04	-0.05	-0.06	-0.08	-0.11	-0.14	-0.17	-0.19	-0.21	-0.23	-0.24	-0.26
1952	-0.27	-0.28	-0.28	-0.28	-0.27	-0.25	-0.24	-0.24	-0.26	-0.28	-0.32	-0.35
1953	-0.39	-0.42	-0.45	-0.48	-0.5	-0.52	-0.53	-0.53	-0.53	-0.51	-0.5	-0.49
1954	-0.47	-0.46	-0.44	-0.42	-0.39	-0.37	-0.36	-0.36	-0.37	-0.38	-0.39	-0.4
1955	-0.41	-0.4	-0.39	-0.38	-0.36	-0.34	-0.31	-0.28	-0.24	-0.21	-0.18	-0.16
1956	-0.15	-0.15	-0.14	-0.13	-0.12	-0.11	-0.11	-0.11	-0.11	-0.11	-0.13	-0.13
1957	-0.13	-0.12	-0.1	-0.07	-0.04	-0.02	0.01	0.02	0.03	0.03	0.02	0
1958	-0.03	-0.05	-0.06	-0.06	-0.04	-0.02	0	0.01	0.03	0.04	0.05	0.05
1959	0.06	0.07	0.09	0.1	0.11	0.12	0.13	0.14	0.15	0.15	0.14	0.13
1960	0.13	0.13	0.13	0.13	0.11	0.06	0	-0.09	-0.17	-0.25	-0.3	-0.33
1961	-0.34	-0.33	-0.32	-0.29	-0.27	-0.25	-0.23	-0.22	-0.2	-0.19	-0.19	-0.17
1962	-0.16	-0.14	-0.13	-0.12	-0.11	-0.1	-0.09	-0.08	-0.08	-0.07	-0.07	-0.08
1963	-0.09	-0.09	-0.09	-0.09	-0.08	-0.06	-0.04	-0.02	0	0.02	0.03	0.03
1964	0.04	0.05	0.07	0.08	0.1	0.11	0.11	0.11	0.11	0.09	0.08	0.07
1965	0.04	0.02	0	-0.03	-0.06	-0.1	-0.14	-0.18	-0.21	-0.24	-0.25	-0.26
1966	-0.26	-0.25	-0.23	-0.22	-0.21	-0.2	-0.2	-0.2	-0.19	-0.16	-0.13	-0.1
1967	-0.08	-0.06	-0.05	-0.05	-0.06	-0.07	-0.1	-0.12	-0.15	-0.17	-0.19	-0.19
1968	-0.19	-0.18	-0.16	-0.14	-0.12	-0.12	-0.12	-0.13	-0.14	-0.15	-0.16	-0.17
1969	-0.19	-0.2	-0.22	-0.23	-0.25	-0.27	-0.3	-0.33	-0.36	-0.38	-0.39	-0.39
1970	-0.37	-0.35	-0.32	-0.28	-0.24	-0.2	-0.17	-0.13	-0.11	-0.09	-0.09	-0.09
1971	-0.1	-0.11	-0.12	-0.13	-0.14	-0.15	-0.16	-0.17	-0.17	-0.18	-0.19	-0.19
1972	-0.2	-0.19	-0.18	-0.18	-0.17	-0.18	-0.18	-0.19	-0.2	-0.21	-0.22	-0.23
1973	-0.22	-0.21	-0.17	-0.12	-0.06	-0.01	0.03	0.05	0.05	0.04	0.02	0
1974	-0.03	-0.05	-0.07	-0.07	-0.06	-0.04	-0.01	0.03	0.07	0.09	0.09	0.09
1975	0.07	0.06	0.05	0.04	0.04	0.03	0.03	0.03	0.02	0.01	0.01	0.01
1976	0.01	0.01	0.02	0.02	0.02	0.01	0.01	-0.01	-0.02	-0.03	-0.03	-0.03
1977	-0.02	-0.02	-0.01	-0.01	0	0.01	0.02	0.04	0.05	0.06	0.06	0.06
1978	0.06	0.06	0.07	0.08	0.08	0.07	0.05	0.02	-0.01	-0.05	-0.09	-0.11
1979	-0.12	-0.12	-0.11	-0.1	-0.09	-0.07	-0.06	-0.05	-0.03	-0.02	-0.01	-0.01
1980	-0.01	-0.01	0	0	0	0	-0.02	-0.04	-0.06	-0.07	-0.08	-0.09
1981	-0.08	-0.07	-0.06	-0.05	-0.05	-0.05	-0.06	-0.07	-0.08	-0.09	-0.08	-0.06
1982	-0.03	0	0.03	0.07	0.1	0.13	0.16	0.18	0.2	0.22	0.23	0.23
1983	0.22	0.2	0.19	0.17	0.17	0.16	0.16	0.16	0.16	0.17	0.17	0.18
1984	0.19	0.19	0.19	0.18	0.17	0.15	0.13	0.12	0.1	0.09	0.09	0.08
1985	0.08	0.09	0.11	0.13	0.16	0.19	0.22	0.24	0.23	0.21	0.17	0.14
1986	0.12	0.1	0.1	0.1	0.09	0.09	0.08	0.07	0.06	0.05	0.04	0.03
1987	0	0	0	0	0	0	0	0	0	0	0	0
1988	0	0	0	0	0	0	0	0	0	0	0	0
1989	0	0	0	0	0	0	0	0	0	0	0	0

Table 8. Basis of comparison Lakes Michigan and Huron water level corrections in ft from IUGLS Plan 177-A (US Army Engineer District, Detroit July 2011).

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1918	-0.16	-0.17	-0.18	-0.20	-0.20	-0.21	-0.21	-0.18	-0.19	-0.16	-0.19	-0.16
1919	-0.15	-0.14	-0.12	-0.11	-0.12	-0.10	-0.08	-0.08	-0.06	-0.05	-0.07	-0.07
1920	-0.09	-0.10	-0.08	-0.11	-0.09	-0.09	-0.10	-0.08	-0.08	-0.07	-0.08	-0.09
1921	-0.07	-0.09	-0.08	-0.08	-0.08	-0.08	-0.06	-0.04	-0.04	-0.05	-0.04	-0.08
1922	-0.05	-0.04	-0.03	-0.05	-0.05	-0.05	-0.05	-0.03	-0.04	-0.04	-0.05	-0.04
1923	-0.04	-0.07	-0.09	-0.08	-0.09	-0.09	-0.09	-0.10	-0.10	-0.09	-0.07	-0.09
1924	-0.10	-0.13	-0.12	-0.11	-0.15	-0.11	-0.12	-0.15	-0.11	-0.12	-0.11	-0.14
1925	-0.14	-0.14	-0.13	-0.13	-0.15	-0.16	-0.16	-0.17	-0.18	-0.19	-0.19	-0.23
1926	-0.22	-0.20	-0.22	-0.26	-0.25	-0.27	-0.24	-0.25	-0.25	-0.22	-0.17	-0.18
1927	-0.17	-0.19	-0.19	-0.19	-0.20	-0.20	-0.18	-0.15	-0.11	-0.13	-0.09	-0.08
1928	-0.10	-0.12	-0.13	-0.15	-0.16	-0.11	-0.11	-0.10	-0.09	-0.09	-0.09	-0.11
1929	-0.10	-0.10	-0.08	-0.11	-0.12	-0.08	-0.09	-0.09	-0.09	-0.06	-0.08	-0.04
1930	-0.06	-0.04	-0.03	-0.03	-0.04	-0.01	-0.02	-0.02	-0.02	-0.03	-0.01	0.00
1931	0.01	-0.03	-0.06	-0.08	-0.07	-0.05	-0.05	-0.07	-0.01	-0.01	0.01	0.00
1932	-0.01	0.03	0.03	0.00	-0.01	0.01	0.01	0.03	0.03	0.04	0.00	0.02
1933	0.04	0.03	0.01	-0.01	-0.02	0.00	-0.01	-0.01	0.00	0.01	0.01	-0.01
1934	-0.01	-0.02	-0.05	-0.06	-0.07	-0.06	-0.08	-0.11	-0.11	-0.08	-0.07	-0.11
1935	-0.12	-0.11	-0.11	-0.12	-0.14	-0.14	-0.14	-0.13	-0.09	-0.10	-0.12	-0.14
1936	-0.16	-0.13	-0.14	-0.16	-0.18	-0.17	-0.16	-0.10	-0.12	-0.11	-0.11	-0.07
1937	-0.11	-0.11	-0.14	-0.11	-0.14	-0.11	-0.11	-0.10	-0.10	-0.06	-0.06	-0.06
1938	-0.05	-0.08	-0.04	-0.09	-0.08	-0.11	-0.10	-0.10	-0.11	-0.12	-0.14	-0.12
1939	-0.10	-0.11	-0.12	-0.10	-0.14	-0.15	-0.14	-0.14	-0.15	-0.15	-0.15	-0.15
1940	-0.13	-0.16	-0.16	-0.15	-0.12	-0.10	-0.09	-0.08	-0.08	-0.08	-0.06	-0.05
1941	-0.08	-0.10	-0.12	-0.12	-0.13	-0.13	-0.10	-0.09	-0.10	-0.10	-0.11	-0.08
1942	-0.10	-0.14	-0.15	-0.18	-0.16	-0.17	-0.14	-0.16	-0.15	-0.13	-0.12	-0.08
1943	-0.10	-0.11	-0.12	-0.13	-0.15	-0.17	-0.16	-0.18	-0.20	-0.21	-0.23	-0.23
1944	-0.21	-0.21	-0.23	-0.22	-0.24	-0.21	-0.19	-0.18	-0.18	-0.20	-0.20	-0.21
1945	-0.18	-0.17	-0.18	-0.20	-0.19	-0.23	-0.20	-0.17	-0.16	-0.16	-0.17	-0.17
1946	-0.19	-0.18	-0.21	-0.21	-0.18	-0.18	-0.19	-0.17	-0.16	-0.14	-0.16	-0.14
1947	-0.14	-0.17	-0.15	-0.19	-0.18	-0.18	-0.18	-0.19	-0.19	-0.20	-0.21	-0.23
1948	-0.24	-0.21	-0.22	-0.25	-0.27	-0.23	-0.22	-0.21	-0.22	-0.19	-0.19	-0.17
1949	-0.16	-0.15	-0.16	-0.20	-0.20	-0.17	-0.17	-0.17	-0.14	-0.16	-0.14	-0.13

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1950	-0.15	-0.15	-0.15	-0.19	-0.18	-0.17	-0.17	-0.17	-0.18	-0.20	-0.20	-0.26
1951	-0.26	-0.23	-0.24	-0.24	-0.25	-0.25	-0.25	-0.22	-0.23	-0.25	-0.26	-0.28
1952	-0.28	-0.27	-0.25	-0.26	-0.24	-0.23	-0.22	-0.21	-0.21	-0.20	-0.21	-0.24
1953	-0.22	-0.22	-0.20	-0.21	-0.23	-0.22	-0.23	-0.23	-0.20	-0.21	-0.22	-0.25
1954	-0.23	-0.23	-0.25	-0.24	-0.25	-0.23	-0.19	-0.19	-0.19	-0.25	-0.22	-0.23
1955	-0.23	-0.22	-0.22	-0.22	-0.20	-0.22	-0.21	-0.19	-0.17	-0.17	-0.15	-0.15
1956	-0.14	-0.17	-0.19	-0.19	-0.21	-0.19	-0.20	-0.18	-0.17	-0.16	-0.17	-0.17
1957	-0.17	-0.19	-0.19	-0.18	-0.17	-0.15	-0.17	-0.13	-0.15	-0.12	-0.14	-0.11
1958	-0.13	-0.16	-0.18	-0.20	-0.18	-0.19	-0.20	-0.17	-0.17	-0.14	-0.16	-0.15
1959	-0.16	-0.17	-0.18	-0.19	-0.19	-0.18	-0.19	-0.17	-0.14	-0.16	-0.19	-0.18
1960	-0.19	-0.19	-0.17	-0.18	-0.23	-0.19	-0.19	-0.22	-0.23	-0.24	-0.25	-0.24
1961	-0.24	-0.22	-0.23	-0.20	-0.21	-0.19	-0.18	-0.18	-0.18	-0.16	-0.16	-0.16
1962	-0.18	-0.15	-0.15	-0.17	-0.18	-0.17	-0.16	-0.15	-0.15	-0.14	-0.13	-0.14
1963	-0.14	-0.15	-0.12	-0.15	-0.16	-0.16	-0.13	-0.13	-0.12	-0.12	-0.11	-0.12
1964	-0.11	-0.12	-0.14	-0.13	-0.18	-0.16	-0.16	-0.16	-0.17	-0.17	-0.19	-0.21
1965	-0.22	-0.23	-0.25	-0.25	-0.28	-0.27	-0.26	-0.27	-0.25	-0.25	-0.23	-0.24
1966	-0.26	-0.25	-0.25	-0.24	-0.26	-0.26	-0.22	-0.21	-0.21	-0.22	-0.18	-0.22
1967	-0.20	-0.20	-0.19	-0.24	-0.22	-0.21	-0.19	-0.19	-0.17	-0.16	-0.19	-0.18
1968	-0.16	-0.20	-0.17	-0.20	-0.17	-0.17	-0.18	-0.18	-0.18	-0.19	-0.19	-0.21
1969	-0.20	-0.21	-0.19	-0.22	-0.24	-0.22	-0.23	-0.23	-0.23	-0.23	-0.23	-0.20
1970	-0.20	-0.20	-0.20	-0.19	-0.19	-0.18	-0.15	-0.13	-0.14	-0.12	-0.13	-0.15
1971	-0.14	-0.13	-0.15	-0.14	-0.14	-0.16	-0.15	-0.16	-0.15	-0.15	-0.15	-0.18
1972	-0.19	-0.16	-0.16	-0.14	-0.17	-0.15	-0.17	-0.17	-0.16	-0.16	-0.19	-0.18
1973	-0.20	-0.18	-0.15	-0.15	-0.11	-0.10	-0.07	-0.08	-0.06	-0.08	-0.07	-0.11
1974	-0.09	-0.11	-0.13	-0.11	-0.11	-0.12	-0.12	-0.09	-0.05	-0.04	-0.06	-0.05
1975	-0.07	-0.07	-0.05	-0.03	-0.08	-0.08	-0.07	-0.05	-0.07	-0.07	-0.08	-0.07
1976	-0.06	-0.05	-0.05	-0.06	-0.06	-0.05	-0.05	-0.06	-0.06	-0.07	-0.04	-0.04
1977	-0.07	-0.08	-0.07	-0.10	-0.08	-0.07	-0.09	-0.07	-0.05	-0.06	-0.09	-0.10
1978	-0.08	-0.08	-0.08	-0.11	-0.10	-0.09	-0.09	-0.08	-0.11	-0.13	-0.12	-0.11
1979	-0.13	-0.13	-0.12	-0.12	-0.14	-0.11	-0.11	-0.11	-0.11	-0.13	-0.11	-0.11
1980	-0.12	-0.10	-0.09	-0.12	-0.09	-0.10	-0.10	-0.10	-0.11	-0.11	-0.10	-0.12
1981	-0.13	-0.10	-0.12	-0.12	-0.11	-0.10	-0.10	-0.10	-0.13	-0.11	-0.10	-0.11
1982	-0.09	-0.09	-0.07	-0.09	-0.07	-0.06	-0.05	-0.06	-0.05	-0.06	-0.05	-0.08

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1983	-0.06	-0.08	-0.08	-0.08	-0.07	-0.07	-0.07	-0.06	-0.07	-0.08	-0.04	-0.05
1984	-0.05	-0.05	-0.04	-0.05	-0.04	-0.06	-0.07	-0.08	-0.10	-0.08	-0.09	-0.05
1985	-0.06	-0.04	-0.06	-0.06	-0.03	-0.01	-0.01	0.01	-0.02	-0.02	-0.06	-0.08
1986	-0.06	-0.06	-0.04	-0.07	-0.05	-0.04	-0.03	-0.03	0.01	-0.05	-0.01	-0.01
1987	-0.03	-0.03	-0.03	-0.03	-0.02	-0.03	-0.04	-0.04	0.00	0.00	-0.01	-0.02
1988	-0.01	-0.02	-0.01	-0.06	-0.04	-0.04	-0.03	-0.05	-0.03	-0.03	-0.04	-0.01
1989	-0.02	-0.03	-0.02	-0.04	-0.01	-0.05	-0.02	-0.03	-0.05	-0.02	-0.02	-0.01
1990	-0.02	-0.04	-0.04	-0.06	-0.06	-0.04	-0.05	-0.04	-0.04	-0.04	-0.02	-0.02
1991	-0.03	-0.03	-0.01	-0.03	-0.01	-0.03	-0.02	-0.02	-0.02	0.00	0.01	-0.03
1992	-0.02	-0.01	-0.02	-0.01	-0.04	-0.02	-0.03	-0.01	-0.01	-0.01	-0.02	-0.01
1993	-0.02	0.00	0.00	-0.01	-0.01	-0.02	-0.03	0.00	0.01	0.01	0.00	-0.01
1994	0.01	0.00	0.00	0.01	-0.01	0.01	-0.03	0.01	0.00	0.00	-0.02	-0.02
1995	-0.01	-0.02	-0.03	0.00	-0.01	-0.02	-0.01	-0.03	-0.01	-0.01	-0.02	-0.03
1996	0.00	0.00	0.00	0.00	0.00	0.01	0.03	0.02	0.02	0.03	-0.02	-0.02
1997	-0.02	0.00	-0.02	-0.01	-0.03	-0.01	-0.04	-0.02	-0.03	-0.04	-0.04	-0.03
1998	-0.03	-0.02	0.00	-0.05	-0.01	0.00	-0.02	-0.03	-0.01	-0.01	-0.01	-0.03
1999	0.00	-0.02	-0.01	-0.02	0.00	-0.01	-0.03	-0.01	0.02	0.01	0.00	-0.03
2000	-0.02	0.00	-0.02	-0.02	-0.02	-0.02	-0.01	-0.02	-0.03	-0.01	-0.02	-0.02
2001	-0.02	-0.02	-0.01	-0.03	-0.01	-0.03	-0.01	-0.02	-0.01	-0.01	-0.01	-0.04
2002	-0.03	-0.02	-0.04	-0.02	-0.03	-0.03	-0.02	-0.03	-0.02	-0.04	-0.03	-0.02
2003	-0.02	-0.03	-0.02	-0.04	-0.05	-0.05	-0.04	-0.04	-0.03	-0.03	-0.05	-0.02
2004	-0.02	-0.03	-0.05	-0.03	-0.01	-0.04	-0.05	-0.03	-0.05	0.00	-0.02	-0.04
2005	-0.04	-0.04	-0.03	-0.03	-0.03	-0.04	-0.03	-0.05	-0.02	-0.03	-0.04	-0.03
2006	-0.03	-0.05	-0.05	-0.06	-0.04	-0.04	-0.03	-0.05	-0.04	-0.05	-0.02	-0.05
2007	-0.05	-0.01	-0.02	-0.05	-0.04	-0.05	-0.03	-0.02	-0.04	-0.04	-0.02	-0.02
2008	-0.03	-0.03	-0.02	-0.05	-0.03	-0.03	-0.03	-0.02	-0.03	-0.01	-0.03	-0.01

3.1.2 Characteristics of long term water levels

The long-term monthly mean lake level time series for the Milwaukee gage is plotted in Figure 4 for the period 1819 - 2010. BOC values have been applied as per Table 7. In addition to the NOAA data, early data for the period 1819 – 1860 were extracted from Quinn and Sellinger (1990) and adjusted to the present datum. Ten peaks have been identified as significant high lake levels and all occur in July – August. The peaks are distributed

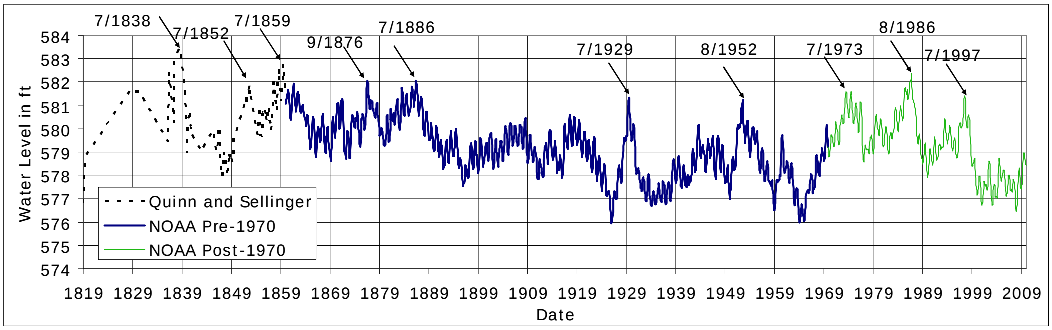

Figure 4. Long-term time series of monthly mean lake levels in ft IGLD 1985 for Milwaukee gage with 10 highest lake levels identified.

fairly continuously throughout the nearly 200 year record with a gap in the late 1800s – early 1900s as the lake level generally decreased over roughly 40 years. The highest lake level occurred in 1838 at lake level 583.4 ft. The next highest occurred in 1859 and the third highest occurred in 1986. It is interesting to note that the long-term water level is cyclic with an average period of roughly 10 years.

The long-term water level time series from all Lake Michigan gages are plotted in Figures 5 - 13. The figures show monthly mean (pink, middle points) and maximum (purple, highest points) water levels for each gage as well as the computed difference between the two (green, lowest line). The mean and maximum correspond to the left-hand vertical axis while the green difference corresponds to the right-hand vertical axis. For cases where no coincident maximum and mean exist, no difference is computed. So for most pre-1950 data, there are no difference data. Only Calumet, Milwaukee, and Mackinaw City gages have pre-1950 difference data. The mostly-storm-induced peaks determined from the peaks-over-threshold analysis to be described later in this report are noted as open circles in the plots. These peaks could be due to a number of physical phenomena including storm surge, seiche, local river flows, runoff, wave setup, and local long-wave effects as well as anthropogenic impacts. For the plots, the pre-1970 mean and maximum values were obtained as monthly means and maxima directly from the historical gage summary because hourly data were not available. Post-1970 monthly mean and maximum values were computed from hourly data. So pre-1970 data are different from post-1970 data and any conclusions drawn must reflect this.

Overall data quality appears to be good. Calumet values between 1930 and 1970 show an offset in the surge measurements that can be seen in Figure 8 “difference” green line. The increased variability in water level signal during

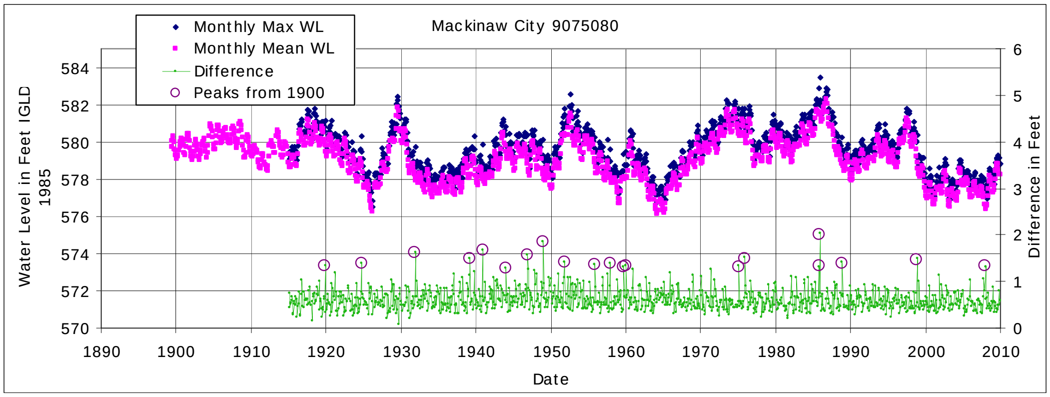

Figure 5. Mackinaw City 9075080 measured water levels 1899 – 2010.

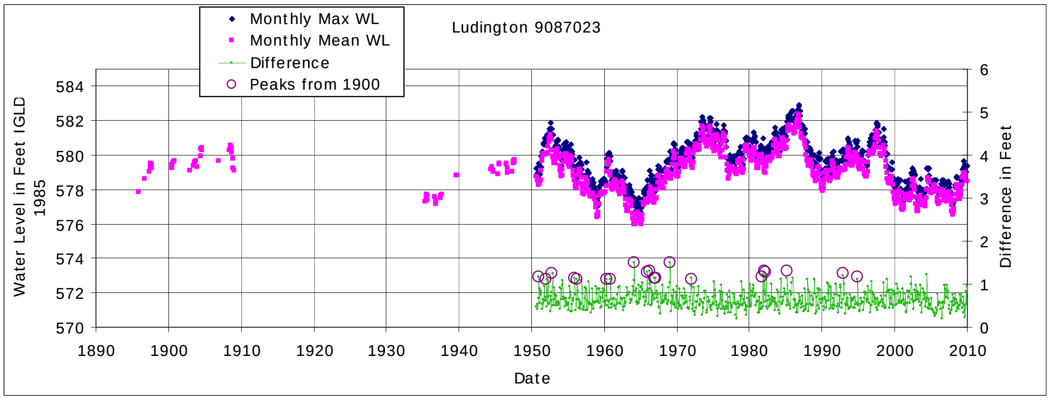

Figure 6. Ludington 9087023 measured water levels 1895 – 2010.

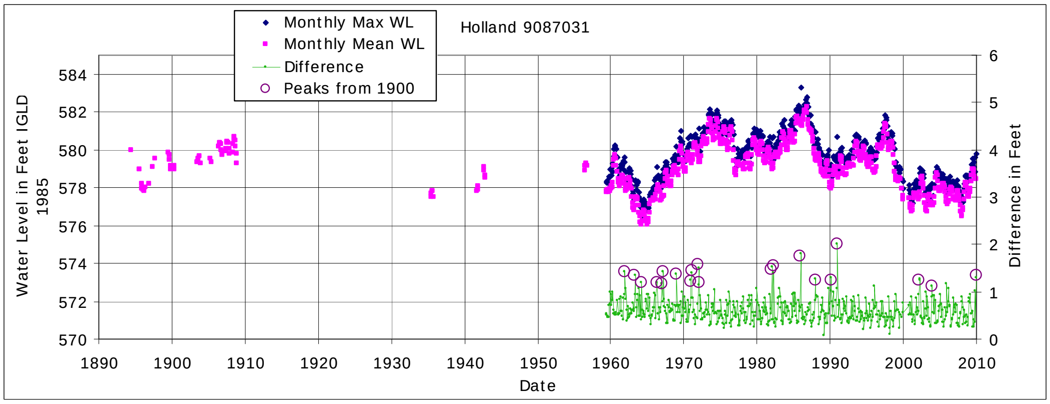

Figure 7. Holland 9087031 measured water levels 1894 – 2010.

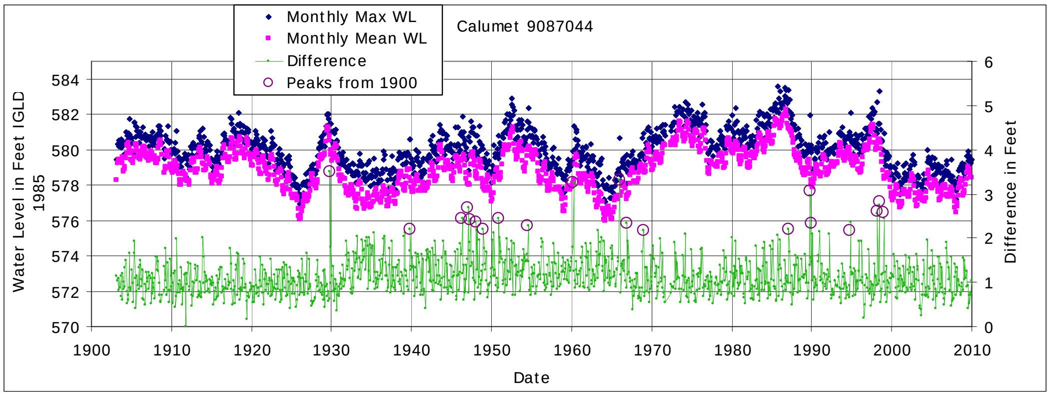

Figure 8. Calumet 9087044 measured water levels 1903 – 2010.

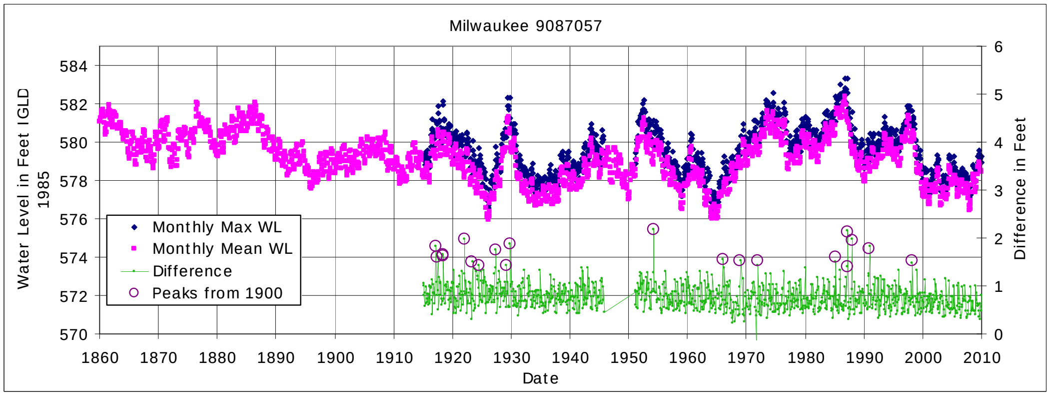

Figure 9. Milwaukee 9087057 measured water levels 1860 – 2010.

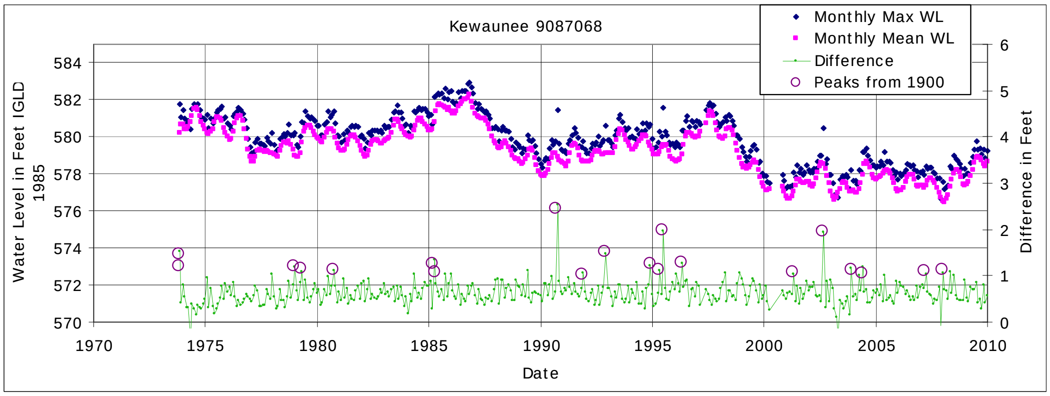

Figure 10. Kewaunee 9087068 measured water levels 1904 – 2010.

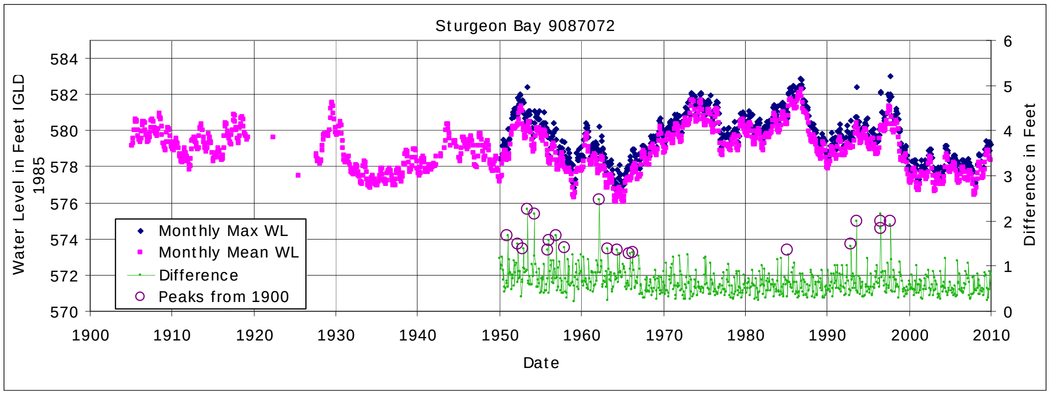

Figure 11. Sturgeon Bay 9087072 measured water levels 1905 – 2010.

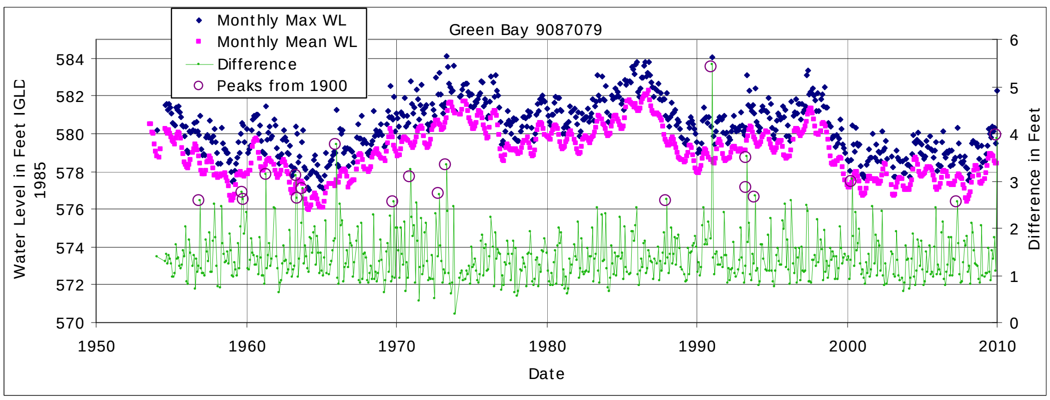

Figure 12. Green Bay 9087078 and 9087079 measured water levels 1954 – 2010.

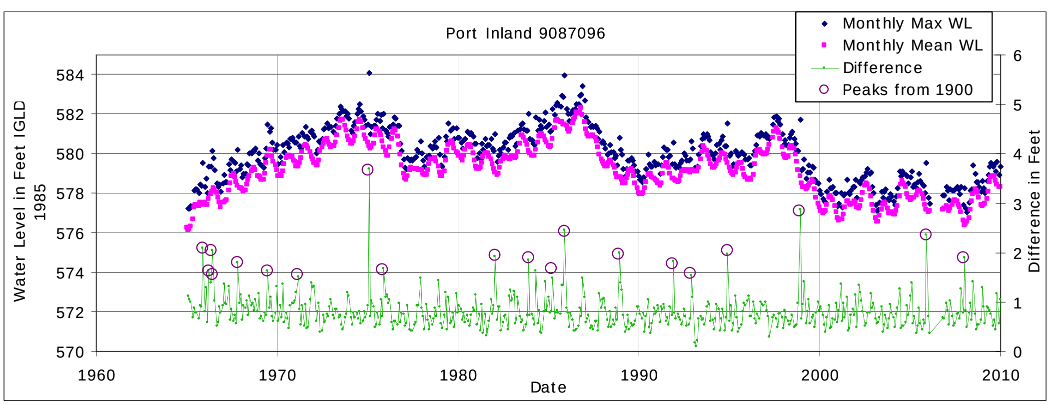

Figure 13. Port Inland 9087096 measured water levels 1964– 2010.

this period is the reason for the offset. This increased variability is a local anthropogenic effect due to variation in water diversion in the Calumet River. The longer records from Calumet, Milwaukee, and Sturgeon Bay gages suggest that the mean signals are stationary with no clear trend over the last 100 years. This is in agreement with the results of Walton and Borgman (1990) who found Lake Michigan long-term lake levels to be

stationary. This is important in that any trend would require special handling in the data processing tasks that follow.

Overall summary statistics of monthly average and maximum water levels are summarized in Table 9. Note that the record lengths vary between stations so these values are not uniform, making the results difficult to compare. For example, the shorter record for Kewaunee is not stationary. Based on the statistics in Table 9, several conclusions can be made. The record length does not have much of an impact on the average or the standard deviation of the average lake levels. Also, the maxima reflect the fetch length exposure of the station. So Calumet, Port Inland, and Green Bay have the highest maxima because they are at the ends of the elongated bodies of water. The central lake stations Ludington, Sturgeon Bay and Kewaunee have the lowest maxima. Visually, the peak surges do not appear to be correlated with long-term lake level variations.

Table 9. Long term Lake Michigan lake level statistics (ft, IGLD 1985).

	Mean of Monthly Averages	Maximum of Monthly Maxima	Minimum of Monthly Averages	Standard Deviation of Monthly Averages
Mackinaw City	579.1	583.5	576.1	1.2
Ludington, MI	579.0	582.9	576.0	1.3
Holland, MI	579.1	583.3	576.0	1.3
Calumet Harbor, IL	578.9	584.0	576.0	1.2
Milwaukee, WI	579.2	583.3	575.9	1.3
Kewaunee, WI	579.2	582.9	576.5	1.3
Sturgeon Bay, WI	579.0	583.0	576.0	1.2
Green Bay, WI	579.0	584.1	575.9	1.3
Port Inland, MI	579.2	584.1	576.1	1.3

3.2 Seasonal trends in water levels

As stated previously, lake levels vary seasonally as a result of precipitation, evaporation, and anthropogenic activities. Figures 14 - 15 show the monthly variation in water level for the gage at Ludington. In Figure 14, the individual points are mean values for that month for a given year. So for each month there are 40 points corresponding to 40 years of data. The mean of all years for a given month has been subtracted from each water level so the vertical axis is deviation from overall mean. It is clear that the range in total water level by month over the 40 years is fairly constant with October – December having slightly greater variability than the other months. In

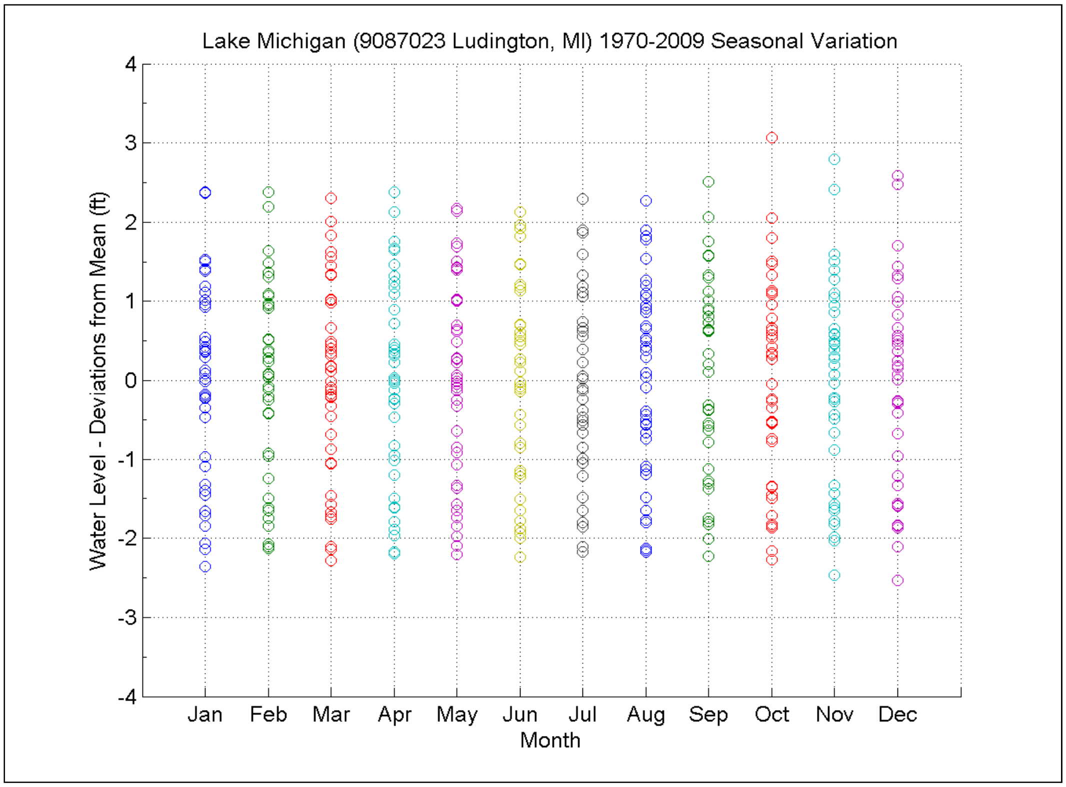

Figure 14. Ludington seasonal variation of measured water levels 1970 – 2010.

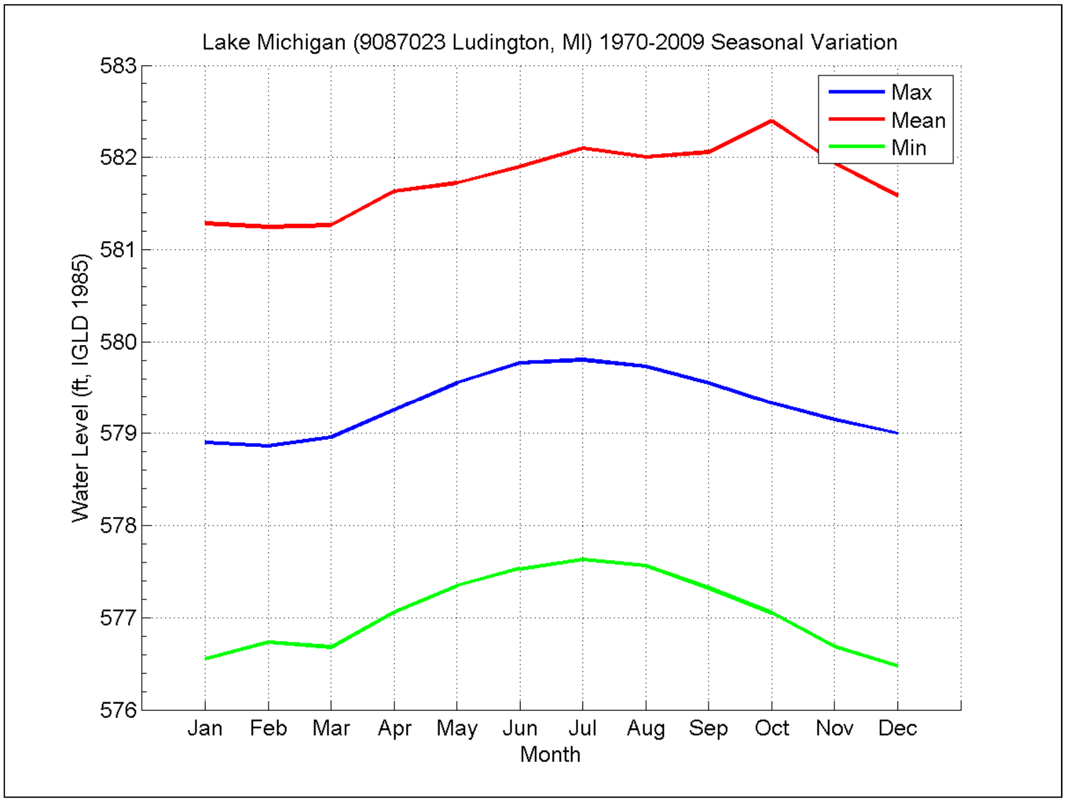

Figure 15. Ludington mean and extremes of measured water levels during the period 1970 – 2010.

Figure 15, mean, maximum, and minimum water levels for each month are plotted. The center blue line is the mean for all years from 1970 through 2009. The red upper and green lower lines are the maximum and minimum water levels by month. The seasonal cycle is clear with a minimum in February and a maximum in July. This seasonal variation was described in FEMA (2009a) as primarily a result of the annual rainfall and evaporation cycle. The second peak in October is a result of storm impacts. Figures 16 and 17 for the Calumet gage are similar to Figures 14 and 15 and show almost identical variability in monthly means. The seasonal characteristics for all gages looked similar to these two examples. Figure 18 shows all years of monthly averages plotted individually for the Ludington gage. In this plot, each year was normalized by the annual average for that year. So the overall range is lower than in the preceding plots. From Figure 18, all years follow the same seasonal trend and the range in monthly average water levels varies from a maximum of 1.7 ft in December-January to a minimum of 0.7 ft in July. Again, all gages were similar.

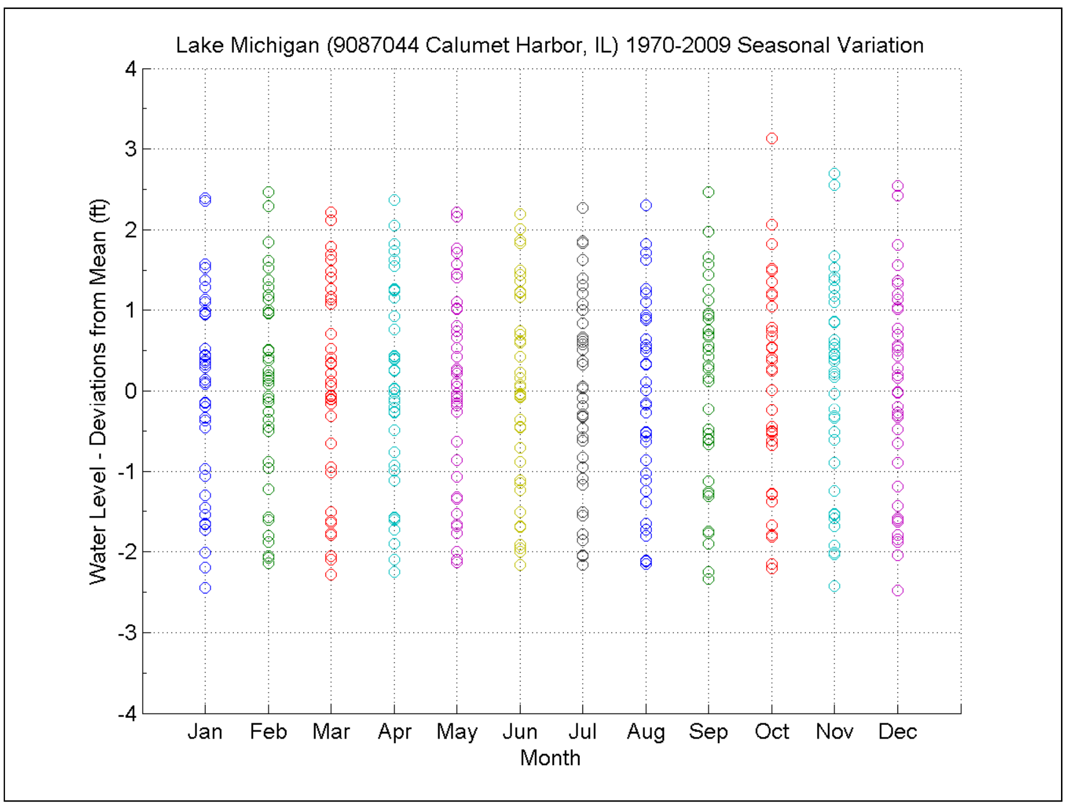

Figure 16. Calumet seasonal variation of measured water levels 1970 – 2010.

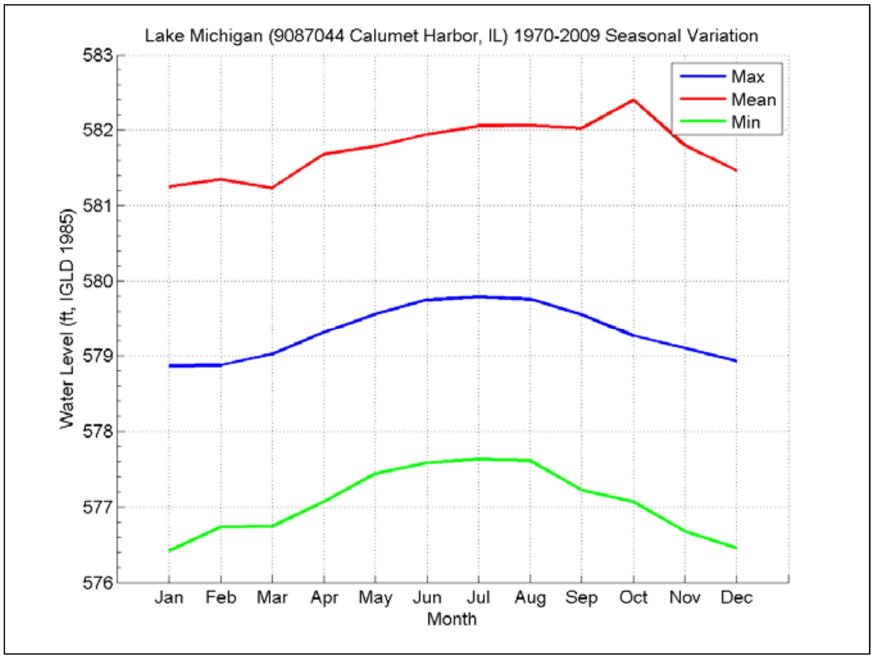

Figure 17. Calumet mean and extremes of measured water levels during the period 1970 – 2010.

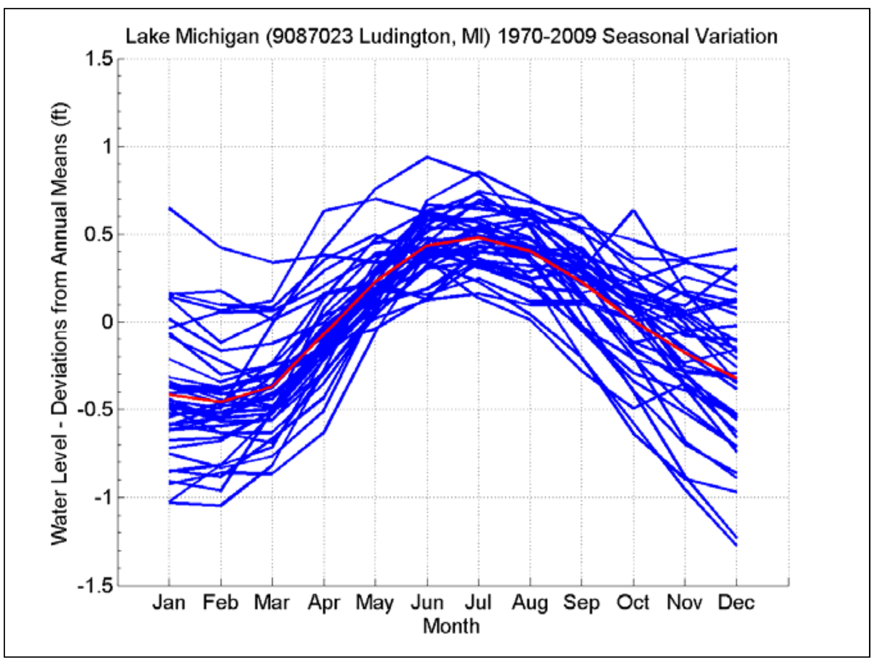

Figure 18. Ludington seasonal variability of measured water levels 1970 – 2010. Monthly mean values have been de-meaned by subtracting the mean for that year and plotted as distinct blue lines. The mean of all years is the central red line.

3.3 Short-term storm-induced water level variation

Short-term fluctuations of as much as five feet in two hours have been observed on the Great Lakes (FEMA 2009a). Generally, high surge events are caused by strong storms. Possible statistical populations of storm events include:

1. Non-convective storms that originate in Canada and move to the east through the lakes region;
2. Non-convective storms that originate in the southern and central Rockies and move east through the lakes region;
3. Convective storm or thunderstorm frontal passages.

Commonly associated with the above events are high winds and atmospheric pressure variations that can generate substantial surge or elevated water levels along the lake boundaries. The surge component produced by high winds results from storm wind producing a shear stress on the surface of the water pushing the water towards the shore. Extra-tropical storms in the lakes region can be high pressure systems or low pressure systems. Low-pressure systems spin counter-clockwise while high pressure systems spin opposite. So winds on the eastern side or leading edge of a low pressure system are typically in the northerly direction while winds on the eastern side of a high pressure system are in the southerly direction. For a typical winter low-pressure storm, it is common for leading winds to be south-easterly transitioning to north-easterly as the storm passes to the south of, or through, the lakes region. Most of the strong winter storms are low pressure systems (Lacke et al. 2007, Niziol and Paone 1991). In addition to the wind-generated surge, there is an elevated water surface dome under the center of low pressure. Rarely this can be enhanced by a high pressure system that is simultaneously over the opposing end of the lake. Several significant storms are analyzed in detail in Appendix B.

Surge produced on one end of a lake will usually correspond to a lowering of the water on the opposite end of the lake and then an ensuing seiching or long period oscillation of the lake surface.

3.3.1 6-min versus 1-hr records

Data recording frequency for water levels changed from 1-hr to 6-min in the 1990s. Presumably, some fast moving storm peaks would not be captured in with 1-hr sampling but might be in the 6-min sampled records. In fact, it is

possible that some frontal systems could produce surge that was only evident in the 6-min records. A simple analysis was done to determine if the 6-min records provided a different set of storms from the 1-hr records.

A peaks-over-threshold analysis was performed over the 6-min period of record for each gage. Recall that the gages started 6-min recording at different times as summarized in Table 3; so the record lengths for Lake Michigan vary from 9.2 to 15.3 years. The highest 100 surge events were selected from each 6-min and hourly record.

In Figure 19, the 6-min and hourly time series are plotted for the Green Bay gage for the storm on 9 Dec 2009. The storm peak occurs at 0900 and is captured by both the 1-hr and 6-min sampling intervals. This peak surge was ranked as the second highest for the Green Bay gage.

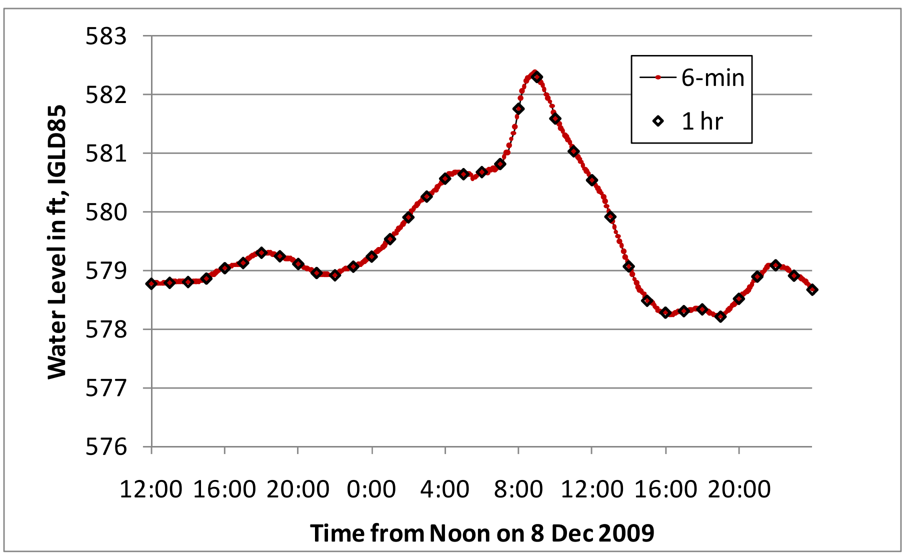

Figure 19. Water level time series for nonconvective storm at Green Bay gage on 9 Dec 2009.

Figure 20 provides an example of a convective storm that occurred on 31 May 1998 on the Calumet gage. The peak surge of 2.82 ft was ranked 5th in the top 20 for Calumet. There is a set down at 12:18 just prior to the event peak. The event peak follows at 13:06. The peak of the storm is well represented by both the 6-min and hourly data. In this case, the preceding set down was not captured in the hourly data.

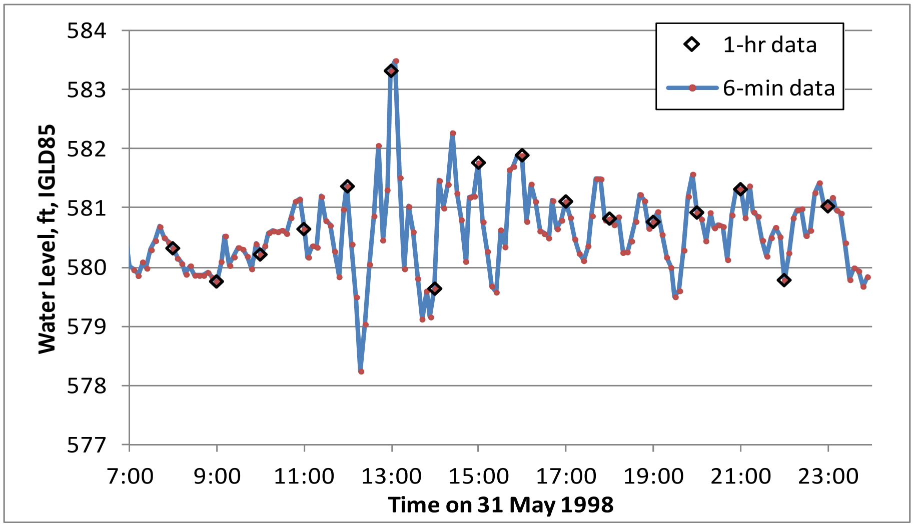

Figure 20. Comparison of 6-min and 1-hr water level measurements for 5 May 1998 storm.

The results of the storm sampling are shown in Figure 21 where peaks from 6-min sampled data are plotted against peaks from 1-hr sampled data for five gages. In general, the families of peaks were similar in the two sets of data. For example, for Calumet, between March 1996 and June 2009, of the total of 100 peaks, 9 were in the 6-min data but not in the hourly data while the remaining 91 were in both groups. The peak surge magnitude of the events not found in both populations was 1.2 – 1.4 ft. The largest event missed was less than 40 percent of the 100 significant surge events during this period. So no larger events were missed. For all stations, the number of events not found in both populations was as follows: Ludington 22, Holland 8, Calumet 14, Milwaukee 13, Kewaunee 36, Sturgeon Bay 26, Green Bay 1, Port Inland 17. The average number of events not found in both populations was 17 percent which is significant. However, because the greater surge events were in both the 6-min and 1-hr populations, the missed events are not likely to produce any impact on the extremal analysis supporting DFIRM production.

Although significant extremal event populations were similar between the 6-min and 1-hr populations, Figure 21 indicates that hourly peaks were consistently biased low for all gages. The bias, computed as root-mean-square deviation, or RMSD, ranges from 0.05 ft for Holland to 0.34 ft for Calumet, but is generally around 0.1 – 0.2 ft for most gages and is fairly uniform over the recorded range of surge values. This deviation in the measured hourly peaks is not all that large but can be corrected when computing total water level and the additional uncertainty from the scatter should be accounted for in an uncertainty analysis as described later in this report.

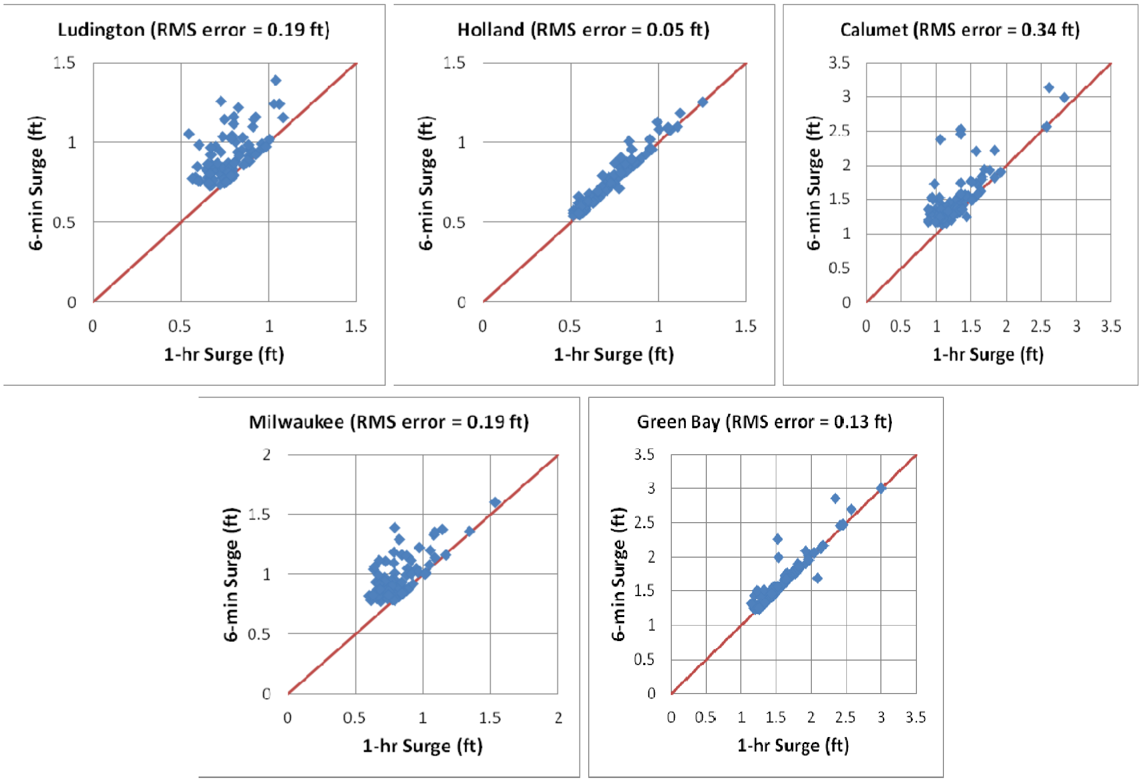

Figure 21. Comparisons of surge populations computed from 6-min and 1-hr water level measurements for Ludington (12 years, top left), Holland (9.3 years, top right), Calumet (14 years, bottom left), and Milwaukee (14 years, bottom right), Green Bay (12 years, top right).

3.3.2 Non-convective storms

Lacke et al. (2007) note that wind data from geographically diverse gages across the Great Lakes show that more than 70 percent of all NCWEs are associated with wind directions in the directional band 180-270 deg. They suggested that this directional preference was related to mid-latitude cyclone dynamics. Niziol and Paone (1991) note that tracks of surface low pressure centers moved from the southwest to northeast across the Great Lakes area. Angel (1996) described the climatology of extra-tropical storms that impact the Great Lakes. Specific non-convective storms are summarized in Appendix B.

3.3.3 Seiche

As described above, if surge occurs on a given shoreline, then a setdown or lowered water level will occur on the opposing shoreline. This oscillation is called seiching. The most common cause of a seiche in the Great Lakes is storm surge on one side of the lake with accompanying set down on the opposite side. The primary harmonic period of this long wave is typically characterized by the Merian formula: $T = 2L/\sqrt{gh}$ where L is the wave

length, *h* is the average depth, and *g* is the acceleration of gravity. Higher harmonics will be produced as well. Lake Michigan is 300 miles long and has an average depth of 300 ft along the long axis. So the mean seiche period for primary mode oscillation along the long axis should be about 9 hrs while the cross-lake primary mode period should be roughly 2 hrs. In Figure 22 we can see long-axis seiche in the time series record from the gage at Port Inland, MI, for the event with peak surge on Nov 20, 1985 at 0100 hrs local time. Here the period of the seiche is roughly nine hours, as predicted by the Merian formula. Typical seiche events can last for 1-3 days with amplitudes of 1-5 ft (FEMA 2009a). In Figure 22, we can see that the seiche persists for nearly 3.5 days from the surge peak.

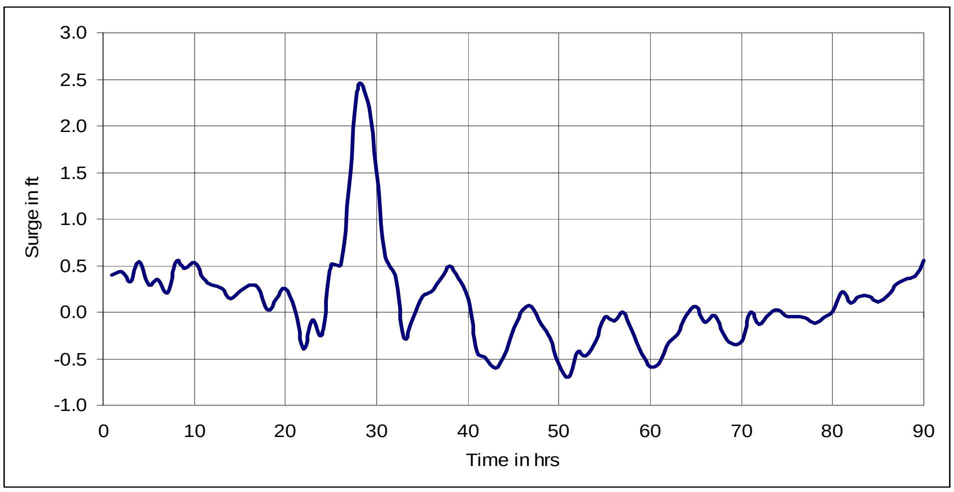

Figure 22. Time series of measurements from Port Inland water level gage showing both storm surge and seiche for storm on Nov 20, 1985.

Green Bay is 100 miles long with an average depth of about 35 ft. The Merian formula predicts that the primary period of oscillation is, again, about nine hours. Figure 23 shows the most severe surge event on Green Bay which occurred on Dec 3, 1990, with a peak at 1300 hrs local time. Again we see a seiche with period of nine hours persisting for several days after the surge peak. It is interesting to note the presence of seiche prior to the event in Green Bay. It is likely that Green Bay surges are partially forced by oscillations of the larger Lake Michigan. The surge peak in Figure 23 appears to include a significant contribution from the background seiche. Taking the average of the seiche at times 35 and 75 hr, the seiche component is roughly 1-ft. It appears that the seiche peak occurs slightly out of phase with the surge peak. For this event the surge peak occurs at time 61 hrs and the seiche peak occurs at 63 hrs. This phase difference results in the background seiche *reducing* the peak surge by about 1-ft but it could have increased it with a small shift in phase.

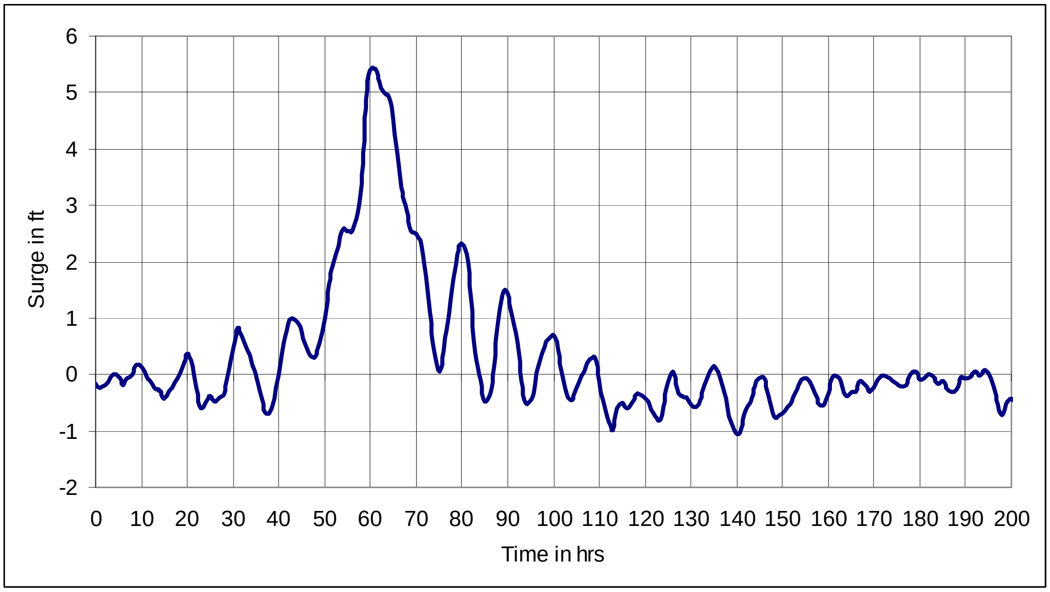

Figure 23. Time series of measurements from Green Bay water level gage showing both storm surge and seiche for storm on Dec 3, 1990.

The Great Lakes do not exhibit astronomical tides of any significance. The Canadian Hydrologic/Hydrographic Service has reported tidal variations on the order of 1-4 cm (0.4 - 1.6 inches). These fluctuations are not significant in the recorded water level signals, being masked by the larger water level variability due to meteorological conditions.

3.3.4 Convective storms

Convective storms are associated with the squall lines of large thunder storms. These storms can produce high winds resulting in high waves and surges. Two convective-storm-related surges, one on 26 June 1954 and the other on 3 Aug 1960, were reported by Ewing et al. (1954) and Platzman (1965). Ewing et al. (1954) termed the 1954 event a surge but the description was more like large waves of between 2- and 4-ft in height. However, Platzman's description led one to believe that a surge occurred as a result of the convective storm. The monthly maximum water level values plotted in Figure 24 show a peak surge in June, 1954, of slightly more than 2-ft on the Calumet gage.

A number of top 20 surges occurred during summer months and were likely associated with convective storms. Gage locations at Calumet, Kewaunee and Sturgeon Bay had several of these events in the top 20 surge list. In Figure 20, we showed an example time series of a convective storm surge event at Calumet. The event passed very quickly and it was improbable that

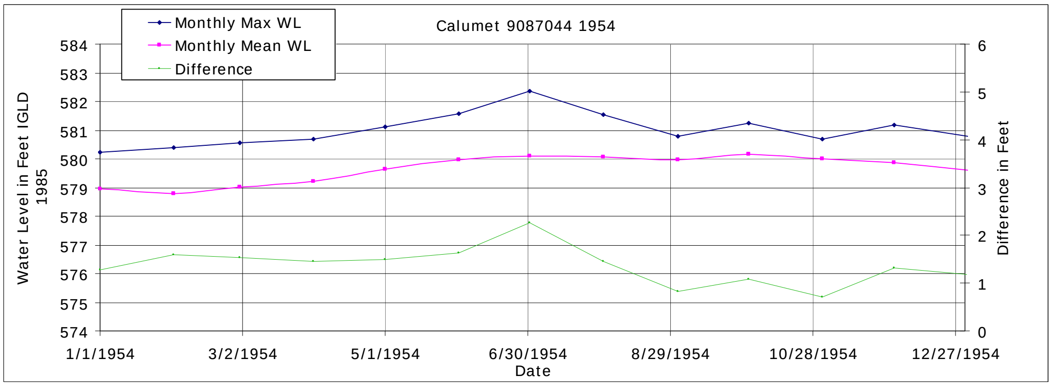

Figure 24. June 1954 surge event at Calumet.

the 6-min and hourly samples would both capture the peak. Figure 25 shows the measured winds, barometric pressure, and wave heights during this period for this storm. Few large surge events occurring in the summer months were observed in the 6-min records.

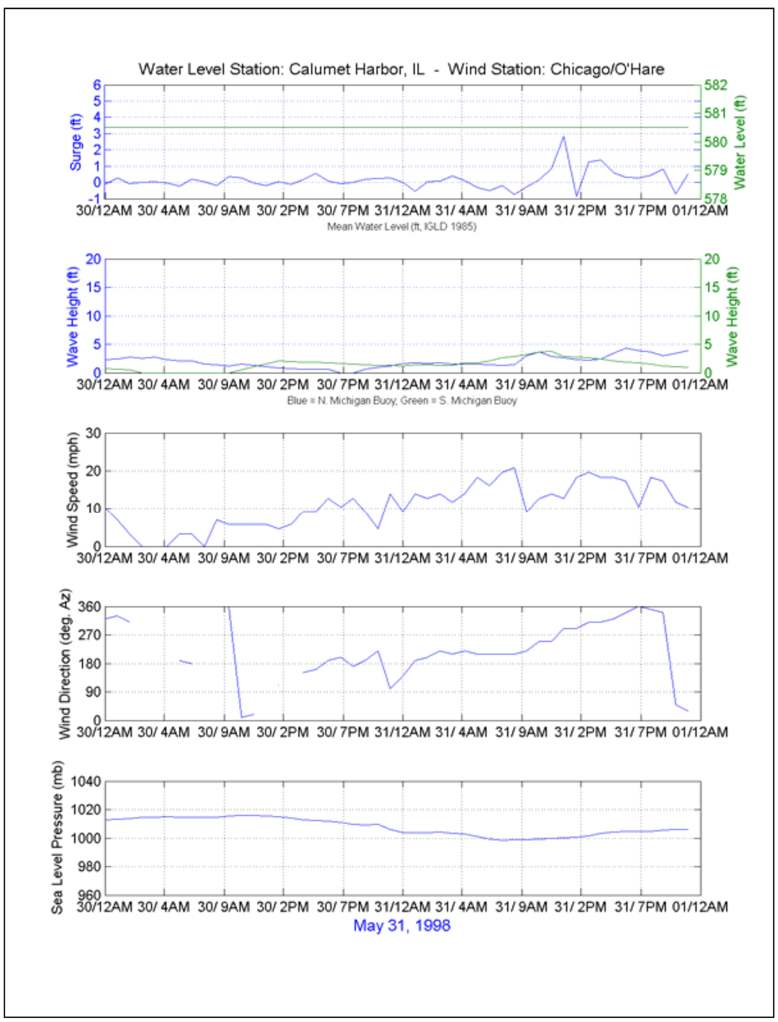

Figure 25. Convective storm at Calumet 31 May 1998.

3.3.5 Other contributions to water levels

Wave breaking, wave setup, wave runup, and wave overtopping are also considerations in determining the total water level as a result of flood inundation. Wave setup and runup are analyzed in Melby (2012) and in FEMA (2009a). Further discussion can be found in USACE EC 1110-2-570.

3.3.6 Statistical correlation between storm surge and longer term water levels

In the previous FEMA Guidelines, the storm event water levels are assumed to have no correlation to the long term water levels. Figures 26 – 31 show correlations between event scale parameters and long term lake levels for several gage locations. The correlation coefficients are shown in the upper right hand corner of each figure. Note that the surge was extracted from the measured water levels prior to the correlation analysis. No correlation of statistical significance was found between long-term water levels and storm events.

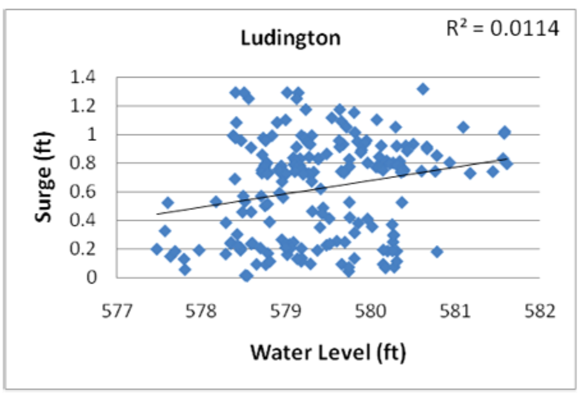

Figure 26. Correlation between surge and long term water levels for Ludington measurements.

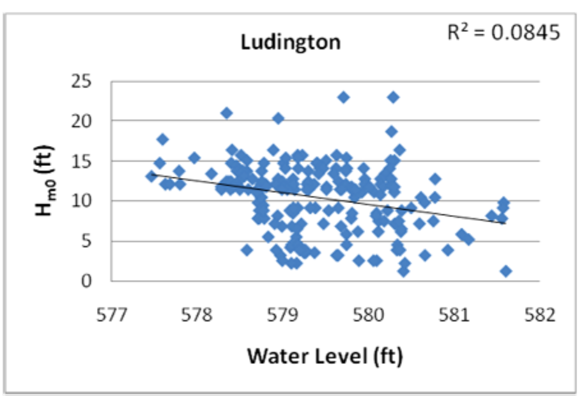

Figure 27. Correlation between WIS offshore wave height and long term water levels for Ludington measurements.

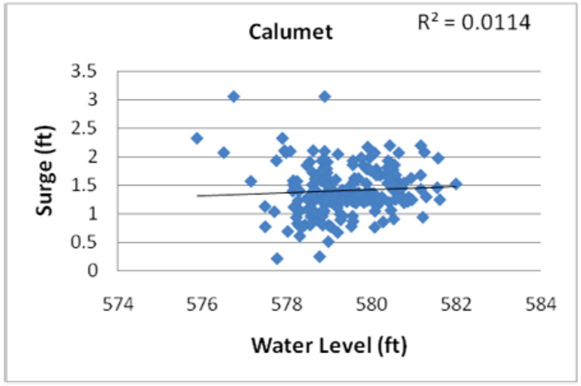

Figure 28. Correlation between surge and long term water levels for Calumet measurements.

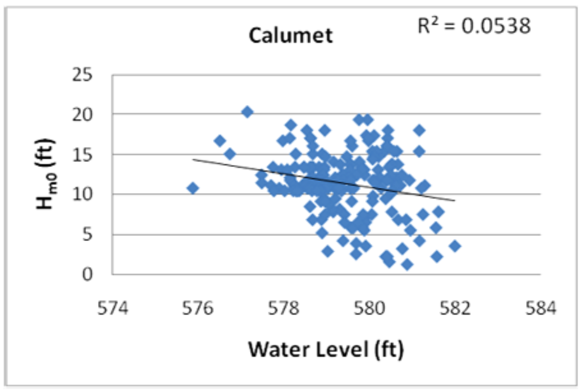

Figure 29. Correlation between WIS offshore wave height and long term water levels for Calumet measurements.

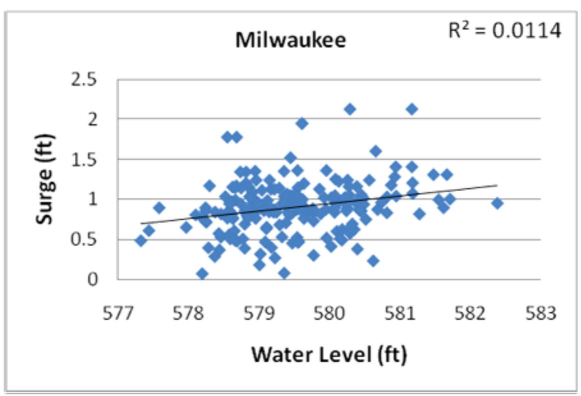

Figure 30. Correlation between surge and long term water levels for Milwaukee measurements.

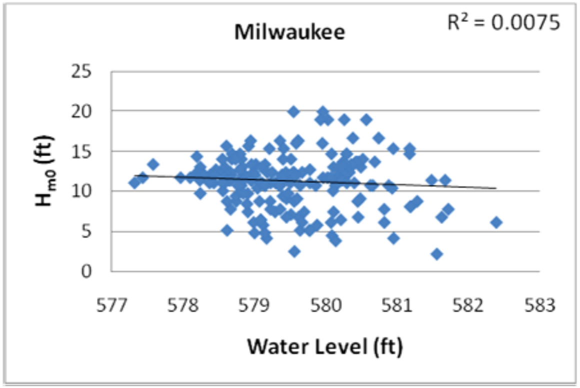

Figure 31. Correlation between WIS offshore wave height and long term water levels for Milwaukee measurements.

4 Coastal Data Characteristics for Lake St Clair

4.1 Long term trends in water levels

BOC adjustment values to account for changes in flow conditions over time due to anthropogenic activities were applied to the water level measurements. These values are shown in Table 10 and were applied to the water level records herein. The 2009 and 2010 water level measurements were used without correction because there were no BOC corrections available during this study.

Table 10. Basis of comparison for Lake St. Clair water level corrections.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1918	1.48	0.89	1.18	1.54	0.92	0.52	0.62	0.52	0.59	0.49	0.46	0.23
1919	-0.07	0.49	0.59	0.59	0.36	0.52	0.62	0.82	0.79	0.62	0.62	0.72
1920	1.61	1.48	0.95	0.72	0.59	0.69	0.72	0.69	0.69	0.69	0.56	0.36
1921	0.13	1.41	0.69	0.43	0.33	0.33	0.46	0.56	0.66	0.72	0.46	0.46
1922	1.48	1.67	0.85	0.26	0.46	0.79	0.66	0.75	0.69	0.59	0.52	0.36
1923	0.82	0.75	0.52	0.56	0.49	0.62	0.62	0.72	0.66	0.52	0.56	0.23
1924	0.75	1.28	0.79	0.39	0.33	0.43	0.43	0.46	0.39	0.39	0.39	0.66
1925	1.05	0.75	0.49	0.16	0.13	0.33	0.33	0.33	0.39	0.36	0.26	0.16
1926	1.54	1.38	0.75	0.30	0.13	0.10	0.13	0.20	0.23	0.13	0.30	0.16
1927	0.72	1.05	0.75	0.16	0.13	0.10	0.23	0.26	0.43	0.30	0.39	0.30
1928	0.89	1.08	1.31	0.23	0.30	0.36	0.30	0.36	0.52	0.52	0.33	0.43
1929	0.72	-0.10	0.23	0.52	0.52	0.62	0.52	0.49	0.43	0.39	0.43	0.66
1930	0.36	0.52	0.26	0.30	0.36	0.46	0.52	0.52	0.52	0.56	0.49	0.43
1931	0.92	2.07	2.00	0.79	0.46	0.52	0.56	0.52	0.75	0.72	0.69	0.79
1932	-0.10	0.07	0.95	0.36	0.46	0.52	0.69	0.79	0.62	0.52	0.30	0.00
1933	0.72	1.44	0.62	0.33	0.43	0.69	0.49	0.43	0.39	0.43	0.30	0.10
1934	1.35	0.85	0.92	0.33	0.30	0.30	0.26	0.49	0.59	0.39	0.43	0.30
1935	0.20	0.98	0.20	0.00	0.16	0.07	0.20	0.30	0.36	0.33	0.07	0.16
1936	1.48	0.36	-0.20	-0.13	0.00	0.10	0.33	0.52	0.49	0.26	0.20	-0.10
1937	0.00	0.59	-0.03	0.13	0.07	0.13	0.16	0.26	0.23	0.20	0.23	-0.49
1938	0.36	-0.16	0.95	0.26	0.13	0.10	0.20	0.16	0.20	0.00	-0.07	0.00
1939	0.20	2.07	1.35	0.07	0.00	0.00	0.07	0.10	0.03	-0.03	-0.07	0.10
1940	0.92	0.85	0.79	-1.87	-0.30	-0.07	0.13	0.20	0.23	0.07	0.23	0.20

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1941	0.23	1.18	0.46	0.23	0.10	0.13	0.26	0.30	0.30	0.07	0.07	0.00
1942	0.59	1.48	0.75	0.00	0.07	0.07	0.13	0.10	0.16	-0.13	0.00	-0.03
1943	0.52	0.59	0.33	0.07	-0.03	-0.03	0.07	-0.07	-0.13	-0.23	-0.26	-0.56
1944	0.36	0.33	0.33	-1.05	-0.30	-0.16	0.00	-0.03	-0.03	-0.20	-0.33	-0.36
1945	-0.79	-0.52	-0.39	-0.33	-0.30	-0.10	-0.13	-0.07	-0.07	-0.13	-0.16	-0.43
1946	0.62	1.54	0.00	-0.30	-0.16	-0.13	-0.03	0.07	0.00	-0.10	-0.13	0.00
1947	0.16	0.07	-0.07	-0.26	-0.13	-0.07	0.03	0.00	-0.13	-0.23	-0.26	-0.26
1948	-0.49	-0.20	-0.33	-0.36	-0.33	-0.13	-0.13	-0.07	-0.10	-0.16	-0.23	-0.26
1949	-0.33	0.03	0.43	-0.23	-0.26	-0.23	-0.13	-0.13	0.03	-0.20	-0.13	-0.10
1950	0.33	0.62	0.52	0.13	0.10	0.26	0.13	0.13	0.00	0.00	-0.07	-0.36
1951	0.26	0.62	-0.07	-0.13	-0.16	-0.07	-0.13	-0.03	-0.13	-0.33	-0.39	-0.66
1952	-0.69	-0.16	-0.43	-0.39	-0.36	-0.36	-0.30	-0.36	-0.26	-0.39	-0.33	-0.36
1953	-0.36	-0.26	-0.36	-0.30	-0.43	-0.33	-0.30	-0.33	-0.23	-0.39	-0.43	-0.33
1954	0.39	0.85	-0.16	-0.30	-0.36	-0.30	-0.26	-0.33	-0.16	-0.46	-0.39	-0.43
1955	-0.33	-0.16	-0.36	-0.36	-0.30	-0.33	-0.26	-0.39	-0.20	-0.13	-0.16	-0.10
1956	0.92	1.08	0.23	0.00	-0.03	0.07	0.03	0.07	0.03	0.00	-0.03	-0.13
1957	1.05	0.59	-0.16	0.00	0.00	0.13	0.13	0.16	0.16	-0.07	0.03	-0.10
1958	0.92	1.21	-0.10	0.46	0.10	0.16	0.16	0.16	0.07	0.10	0.00	-0.16
1959	0.26	0.20	0.00	-0.13	-0.13	-0.16	-0.03	-0.03	-0.03	-0.03	-0.03	0.00
1960	0.49	0.98	0.13	-0.20	-0.16	-0.13	-0.10	-0.07	-0.16	-0.39	-0.36	-0.69
1961	-1.02	-0.43	-0.66	-1.18	-0.49	-0.30	-0.10	-0.10	-0.03	-0.03	-0.13	-0.03
1962	-0.33	0.00	-0.20	-0.16	-0.16	-0.07	0.00	0.03	0.00	-0.07	-0.16	-0.10
1963	-0.16	-0.10	-0.10	-0.13	-0.13	-0.03	0.13	0.16	0.13	0.07	0.00	0.00
1964	-0.03	-0.13	-0.10	-0.10	-0.16	0.03	0.13	0.13	0.10	0.07	-0.10	-0.13
1965	-0.20	-0.20	-0.23	-0.36	-0.36	-0.30	-0.23	-0.20	-0.23	-0.26	-0.33	-0.33
1966	-0.46	-0.39	-0.39	-0.39	-0.43	-0.33	-0.23	-0.16	-0.20	-0.20	-0.30	-0.33
1967	-0.30	-0.26	-0.30	-0.39	-0.36	-0.26	-0.16	-0.16	-0.16	-0.16	-0.33	-0.30
1968	-0.23	-0.36	-0.26	-0.30	-0.30	-0.16	-0.16	-0.13	-0.16	-0.20	-0.30	-0.30
1969	-0.26	-0.39	-0.36	-0.43	-0.46	-0.33	-0.30	-0.30	-0.33	-0.36	-0.49	-0.49
1970	-0.26	-0.43	-0.39	-0.39	-0.36	-0.30	-0.16	-0.10	-0.13	-0.13	-0.23	-0.26
1971	-0.30	-0.13	-0.26	-0.26	-0.26	-0.20	-0.13	-0.10	-0.13	-0.20	-0.23	-0.30
1972	-0.33	-0.36	-0.30	-0.30	-0.36	-0.20	-0.16	-0.16	-0.23	-0.26	-0.43	-0.39
1973	-0.43	-0.43	-0.43	-0.39	-0.33	-0.20	-0.10	-0.07	-0.03	-0.13	-0.10	-0.20
1974	-0.20	-0.20	-0.30	-0.23	-0.30	-0.16	-0.13	-0.07	-0.03	0.00	-0.10	-0.13
1975	-0.10	-0.13	-0.07	-0.07	-0.13	-0.07	0.00	0.07	-0.03	-0.07	-0.13	-0.07
1976	-0.16	0.00	-0.13	-0.07	-0.10	0.03	0.10	0.07	0.07	0.00	-0.03	-0.03

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1977	0.00	-0.10	0.00	-0.07	-0.07	0.03	0.10	0.10	0.13	0.07	-0.07	-0.03
1978	-0.13	-0.10	-0.10	-0.16	-0.13	-0.03	0.00	0.07	0.00	-0.07	-0.20	-0.10
1979	-0.23	-0.13	-0.16	-0.20	-0.20	-0.07	-0.03	-0.03	-0.03	-0.13	-0.20	-0.16
1980	-0.23	-0.16	-0.10	-0.23	-0.16	-0.10	0.00	-0.03	-0.07	-0.10	-0.16	-0.23
1981	0.00	-0.20	-0.16	-0.13	-0.20	-0.03	0.00	0.00	-0.03	-0.10	-0.13	-0.16
1982	-0.13	-0.10	-0.13	-0.13	-0.07	0.03	0.07	0.10	0.13	0.07	-0.03	-0.10
1983	-0.07	-0.03	-0.07	-0.10	-0.10	0.00	0.07	0.03	0.03	-0.03	-0.10	-0.10
1984	-0.13	0.00	-0.10	0.03	-0.07	0.00	0.03	0.07	0.00	-0.07	-0.16	-0.03
1985	-0.13	-0.07	-0.13	-0.13	-0.10	0.00	0.07	0.07	0.00	0.03	-0.13	-0.10
1986	-0.20	-0.13	-0.10	-0.16	-0.13	-0.10	-0.03	-0.03	0.03	-0.13	-0.07	-0.10
1987	-0.13	-0.13	-0.13	-0.16	-0.13	-0.07	-0.07	-0.07	-0.03	0.00	-0.13	-0.16
1988	-0.10	-0.10	-0.10	-0.20	-0.16	-0.10	-0.07	-0.07	-0.07	-0.13	-0.20	-0.13
1989	-0.20	-0.26	-0.10	-0.20	-0.13	-0.10	-0.03	-0.07	-0.10	-0.10	-0.13	-0.13
1990	-0.16	-0.20	-0.20	-0.23	-0.20	-0.10	-0.10	-0.10	-0.10	-0.10	-0.16	-0.10
1991	-0.23	-0.13	-0.13	-0.16	-0.13	-0.16	-0.10	-0.07	-0.13	-0.10	-0.10	-0.16
1992	-0.20	-0.16	-0.13	-0.13	-0.16	-0.10	-0.07	-0.07	-0.07	-0.07	-0.13	-0.07
1993	-0.16	-0.07	-0.07	-0.13	-0.13	-0.13	-0.13	-0.10	-0.10	-0.07	-0.10	-0.10
1994	0.00	-0.10	0.03	-0.03	-0.07	0.03	-0.10	-0.03	0.00	-0.03	-0.07	-0.03
1995	-0.03	-0.03	0.00	0.00	0.00	0.00	-0.03	-0.07	-0.03	-0.03	-0.07	-0.13
1996	0.07	-0.07	0.00	0.07	-0.10	0.03	0.03	0.03	0.07	0.00	0.00	0.00
1997	0.00	0.07	-0.03	-0.07	-0.07	-0.03	-0.07	-0.03	-0.07	-0.07	-0.03	-0.07
1998	-0.03	-0.03	0.00	-0.07	-0.07	0.00	-0.03	-0.07	-0.03	0.00	-0.03	-0.03
1999	-0.07	0.00	-0.03	-0.07	-0.03	-0.03	-0.07	-0.03	-0.03	-0.07	-0.07	-0.07
2000	-0.13	0.07	-0.13	-0.07	-0.07	-0.07	-0.03	-0.07	-0.07	-0.03	-0.03	0.00
2001	-0.13	-0.03	-0.03	-0.10	-0.03	-0.07	-0.03	-0.03	-0.03	-0.03	0.00	-0.13
2002	-0.03	-0.10	-0.10	-0.10	-0.07	-0.07	-0.07	-0.07	-0.03	-0.10	-0.10	-0.03
2003	-0.07	-0.16	0.03	-0.13	-0.07	-0.13	-0.10	-0.10	-0.10	-0.07	-0.10	-0.07
2004	-0.10	-0.10	-0.10	-0.13	-0.07	-0.13	-0.10	-0.07	-0.13	-0.07	-0.07	-0.07
2005	-0.13	-0.10	-0.10	-0.10	-0.07	-0.10	-0.07	-0.07	-0.07	-0.10	-0.10	-0.10
2006	-0.10	-0.13	-0.16	-0.13	-0.13	-0.13	-0.10	-0.10	-0.13	-0.10	-0.07	-0.13
2007	-0.16	-0.13	-0.07	-0.13	-0.16	-0.10	-0.10	-0.07	-0.10	-0.10	-0.10	-0.10
2008	-0.07	-0.13	-0.03	-0.10	-0.03	-0.07	-0.10	-0.07	-0.07	-0.03	-0.07	0.03

The long-term monthly mean water level time series from Lake St. Clair gage at Windmill Point is plotted in Figure 32. This is the longest recorded times series for Lake St Clair and suggests a stationary lake level for the last 100 years.

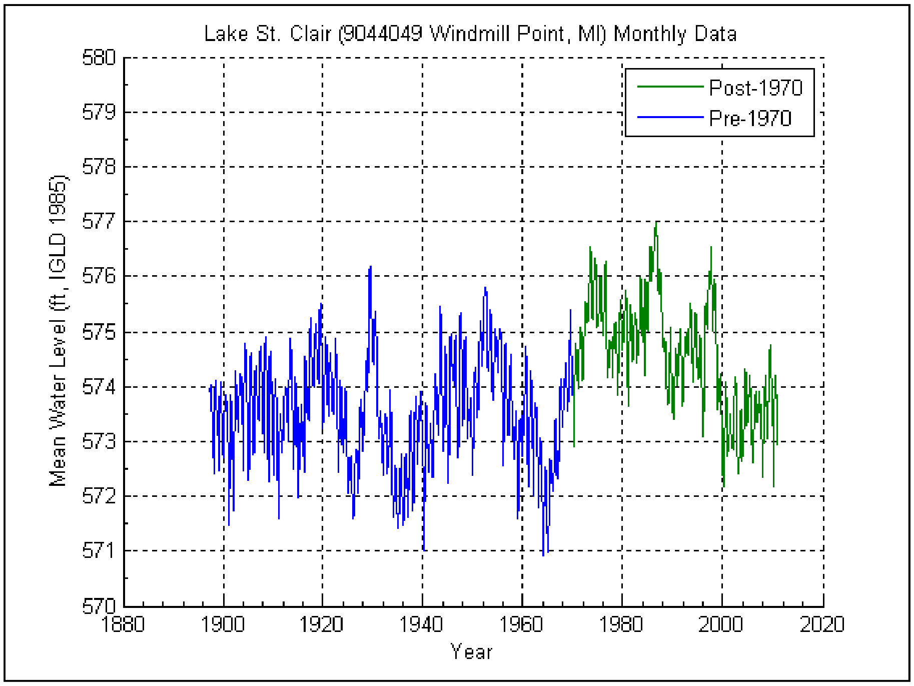

Figure 32. Long-term time series of monthly mean lake levels for Windmill Point gage station.

The long-term water level time series from Lake St. Clair gages are plotted in Figures 33 - 36. The figures show monthly mean (pink, middle points) and maximum (purple, upper points) water levels for each gage as well as the computed difference between both (green, bottom line). The mean and maximum correspond to the left-hand vertical axis while the green difference corresponds to the right-hand vertical axis. For cases where no coincident maximum and mean exist, no difference is computed. So for most pre-1950 data, there are no difference data.

The mostly-storm-induced peaks determined from the peaks-over-threshold (POT) analysis to be described later in this report, are noted as open circles in the plots. The storms selected were the top 20 surge events of each station.

For the plots, the pre-1970 mean and maximum values were obtained as monthly means and maxima directly from the historical gage summary because hourly data were not available. Post-1970 monthly mean and maximum values were computed from hourly data. Overall data quality appears to be good.

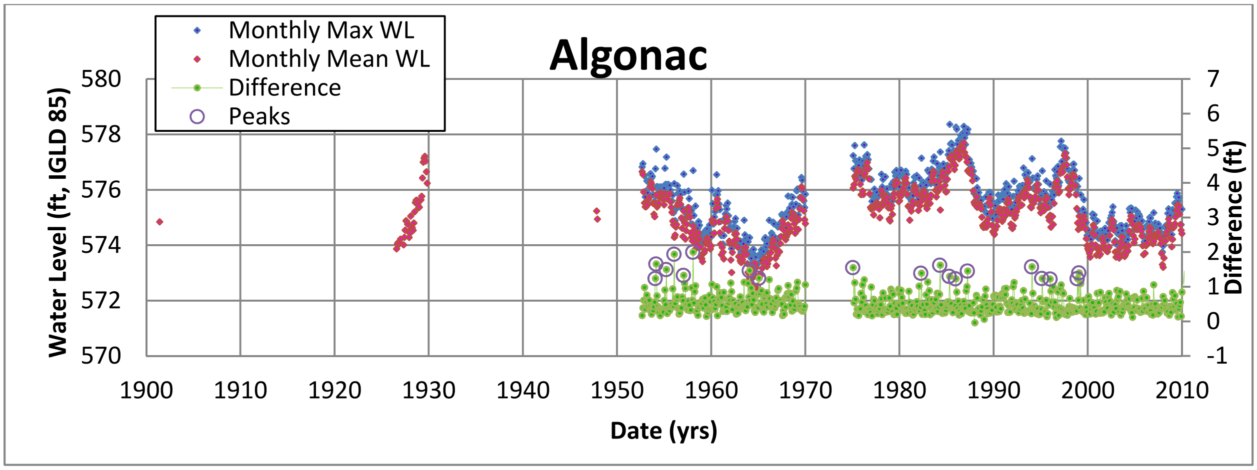

Figure 33. Algonac measured water levels 1901 – 2010.

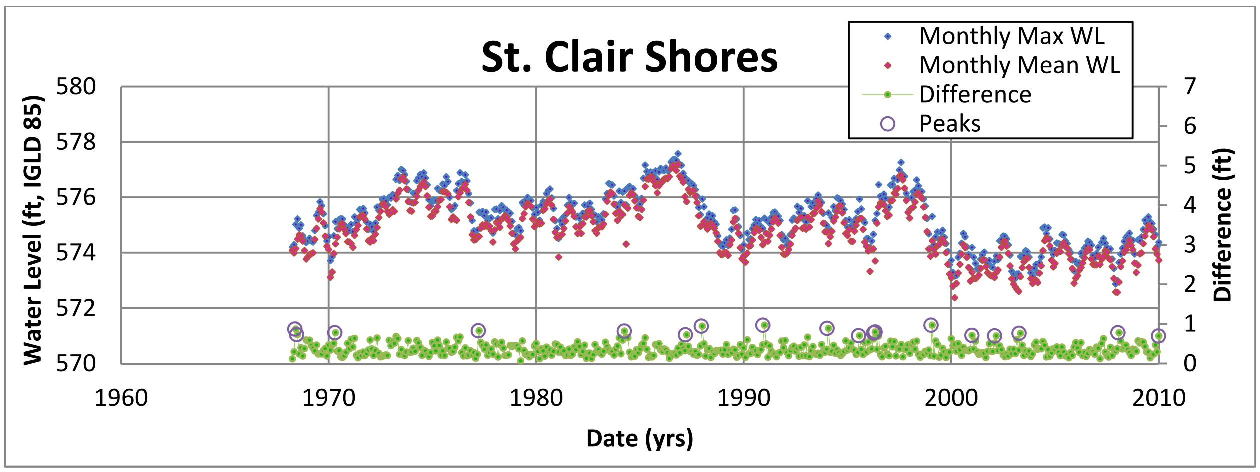

Figure 34. St. Clair Shores measured water levels 1968 – 2010.

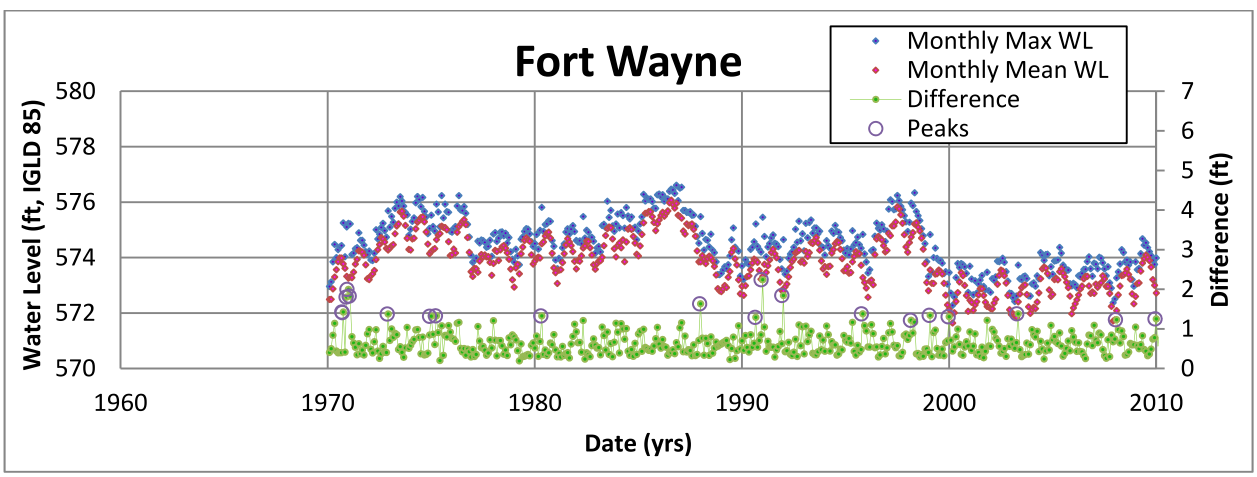

Figure 35. Fort Wayne measured water levels 1970 – 2010.

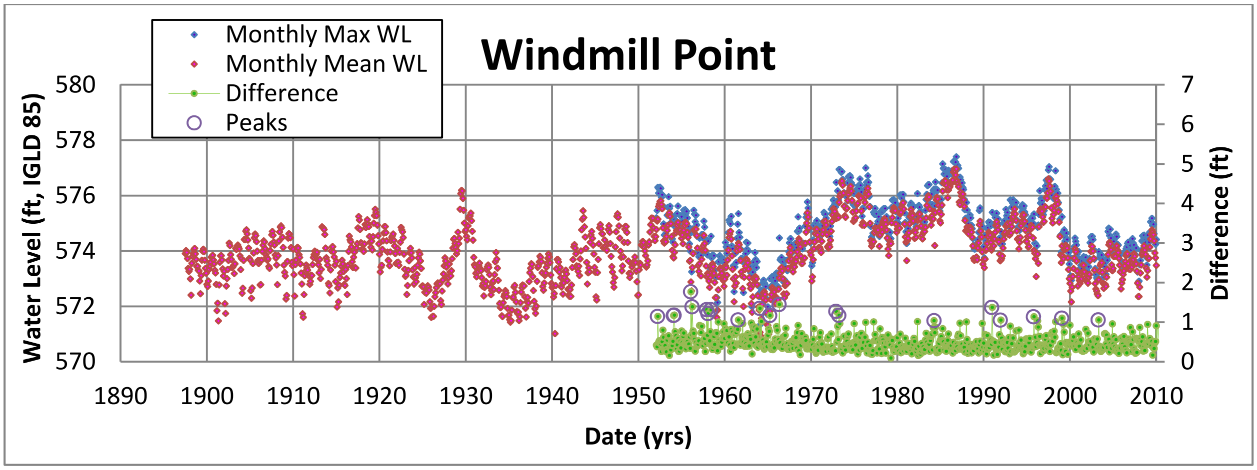

Figure 36. Windmill Point measured water levels 1897 – 2010.

Overall summary statistics of monthly average and maximum water levels are summarized in Table 11. As for Lake Michigan, record lengths are not uniform between stations making the results difficult to compare. Based on the statistics in Table 11, the record length does not impact the average or the standard deviation of the average lake levels.

Table 11. Long-term Lake St. Clair lake level statistics (ft, IGLD 1985)

Station	Mean of Monthly Averages	Maximum of Monthly Maxima	Minimum of Monthly Averages	Standard Deviation of Monthly Averages
Algonac	575.06	578.37	572.39	1.04
St. Clair Shores	574.80	577.58	572.33	1.00
Fort Wayne	573.83	576.61	571.65	0.94
Windmill Point	573.93	577.40	570.94	1.08

4.2 Seasonal trends in water levels

As for Lake Michigan, Lake St Clair lake levels vary seasonally as a result of precipitation, evaporation, and anthropogenic activities. Figure 37 shows an example of monthly variation in water level. The individual points were computed as monthly means from Gaussian-smoothed time series demeaned by subtracting mean from all years. For each month there are 41 points corresponding to 41 years of data. The mean of all years for a given month has been subtracted from each water level so the vertical axis is deviation from overall mean. The range in total water level by month over the 41 years is fairly constant with October–December having slightly greater variability than the other months.

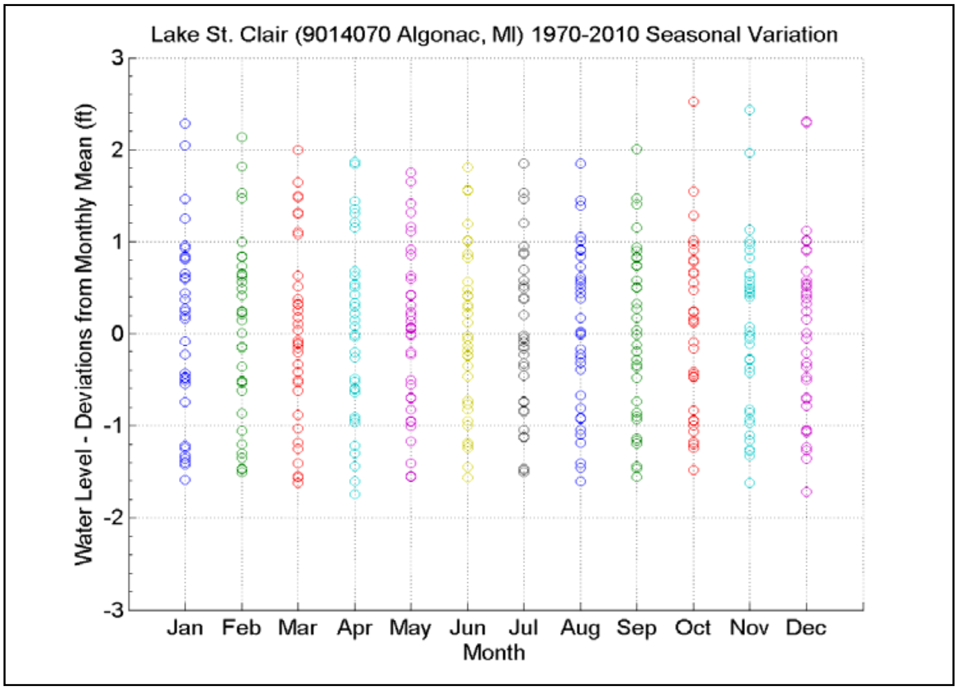

Figure 37. Algonac seasonal variation of measured water levels 1970 – 2010.

In Figure 38, mean and extremes of measured water levels for each month are plotted for Algonac. The center blue line is the mean for all years from 1970 through 2010. The red upper and green lower lines are the maximum and minimum water levels by month. The seasonal cycle is clear with a minimum in February and a maximum in July illustrating the impact of annual rainfall and evaporation cycle. The second peak in October is a result of storm impacts.

Figure 39 shows all years of monthly averages plotted individually for each gage station. In this plot, each year was normalized by the annual average for that year and plotted as distinct blue lines. So the overall range is lower than in the preceding plots. The mean of all years is the central red line. As for Lake Michigan, all years follow the same seasonal trend and the range in monthly average water levels varies from a maximum of 2.4 ft in the winter (December-January) to a minimum of 0.6 ft in the summer (June-July).

Table 12 shows the deviations from annual mean for each gage.

4.2.1 NOAA water level measurements and datum errors

Gibson and Gill (1999) discuss that typical measurements errors are 0.3 ft at 95 percent confidence level; likewise, datum errors are typically 0.6 ft. The total of 0.9 ft at 95 percent confidence level is equivalent to a standard error of 0.5 ft.

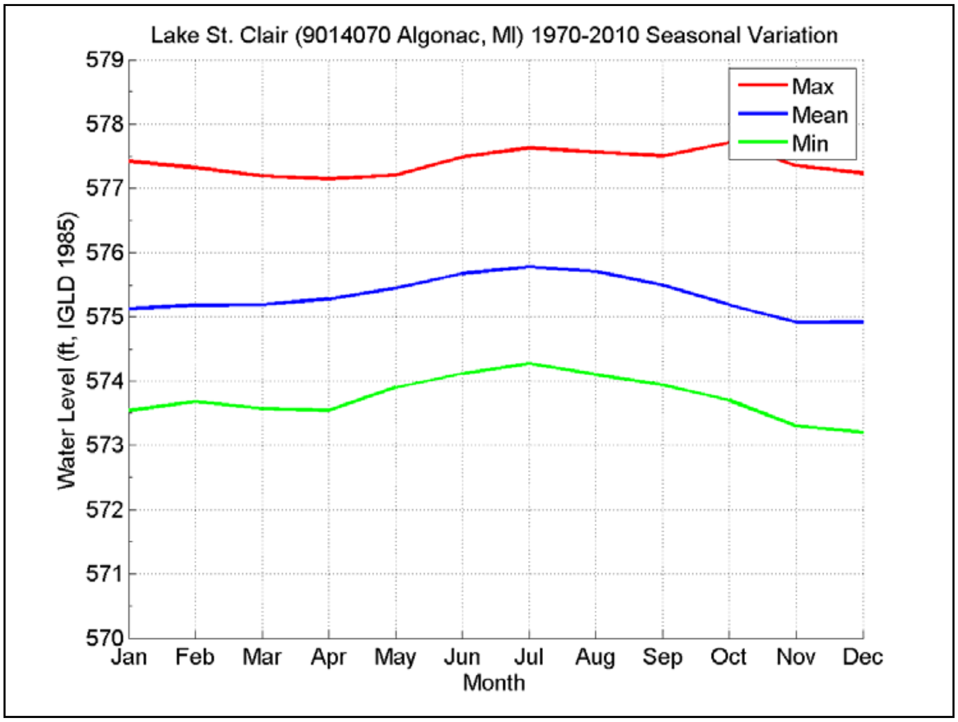

Figure 38. Algonac mean and extremes of measured water levels during the period 1970 – 2010.

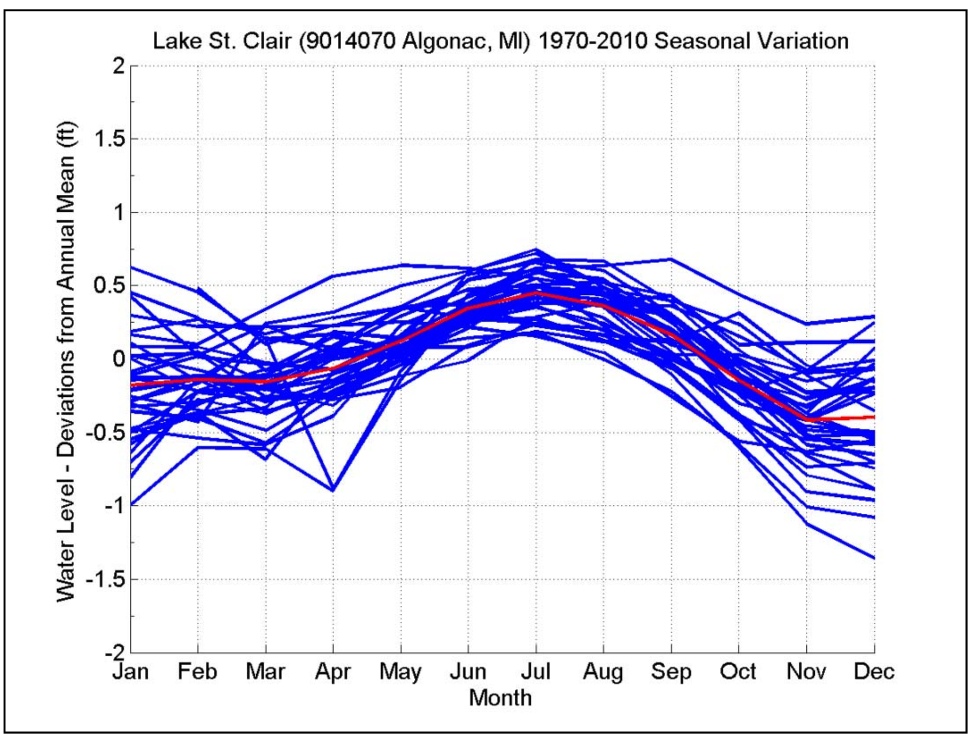

Figure 39. Algonac seasonal variability of measured water levels 1970 – 2010.

Table 12. Seasonal Variation – Deviations from Annual Mean in feet.

Station	Station Number	Summer	Winter
Algonac, MI	9014070	0.6	1.7
St Clair Shores, MI	9034052	0.6	2.4
Fort Wayne, MI	9044036	0.6	2.1
Windmill Point, MI	9044049	0.6	2.3

4.2.2 Six-min versus 1-hr records

Data recording frequency for water levels changed from 1-hr to 6-min in the 1990s, as was discussed for Lake Michigan. Again, an analysis was done to determine the bias from the older slower sampling rate.

A peaks-over-threshold analysis was completed over the 6-min period of record for each gage. The record length was approximately 14 years for all gages, except for the Windmill Point station, which was 11 years. The highest 100 surge events were selected from each 6-min and hourly record. The results of the analysis are shown in Figure 40. The bias, computed as root-mean-square deviation, or RMSD, ranges from 0.03 ft for Fort Wayne to 0.06 ft for Algonac and St. Clair Shores indicating that hourly peaks were consistently biased low for all gages. However, the bias was very small and the families of peaks were similar in the two sets of data.

4.2.3 Seiche

In Figure 41 we see seiche in the time series record from the gage at Fort Wayne for the event with peak surge on 14 April 1980. Here the period of the seiche is roughly 14 hrs and we can see that the seiche persists for nearly 2 days from the surge peak.

There is another example at Fort Wayne in Figure 42. It shows the event with peak surge on 27 February 1997. Once again the period of the seiche is approximately 14 hrs. There is a set down at 115 hrs, just before the surge peak. For Lake St. Clair, the seiche amplitude was always less than the surge and there was no evidence the seiche produced an effect on the surge that would not be accounted for in the hydrodynamic modeling.

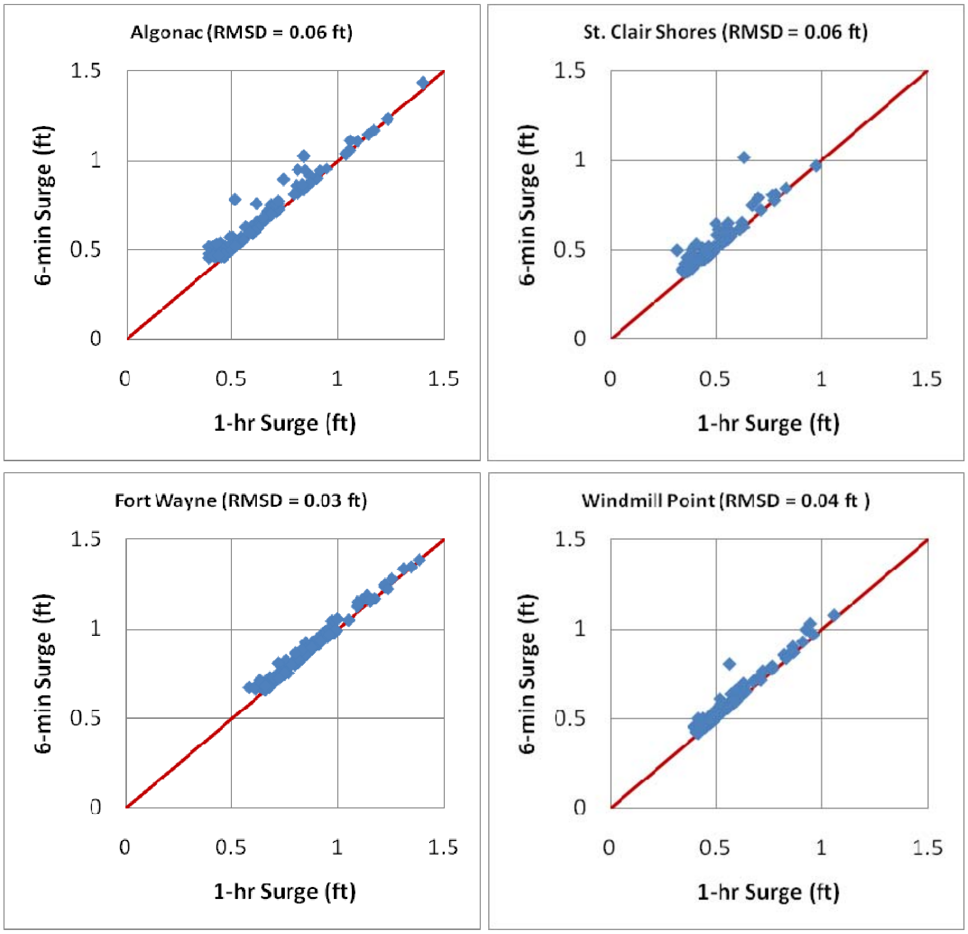

Figure 40. Comparisons of surge populations computed from 6-min and 1-hr water level measurements for Lake St. Clair gages.

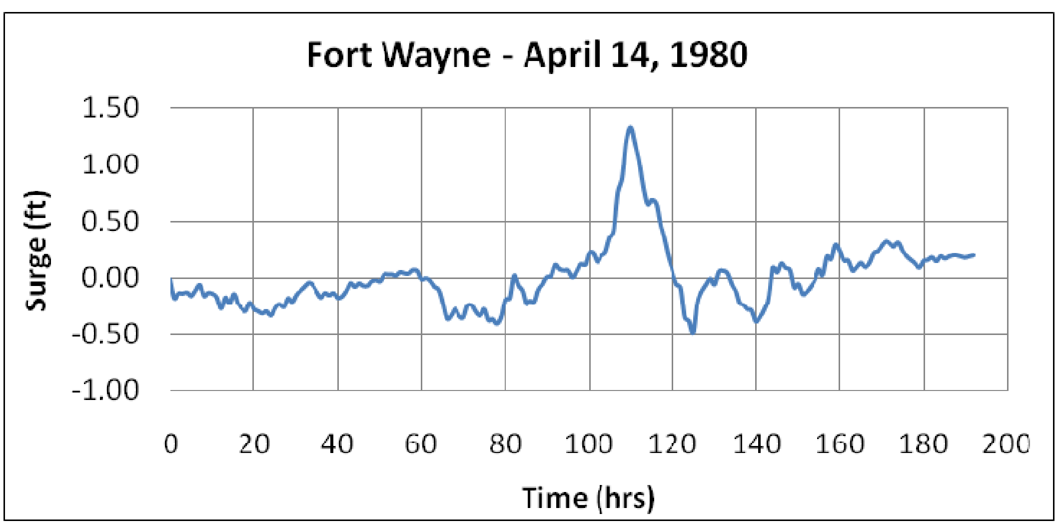

Figure 41. Time series of measurements from Fort Wayne water level gage showing surge and seiche for storm on April 14, 1980.

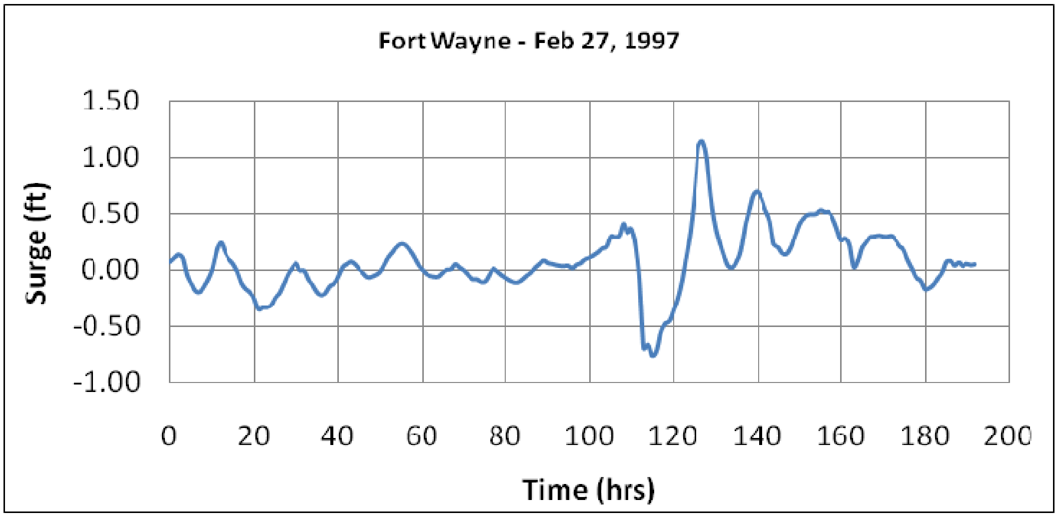

Figure 42. Time series of measurements from Fort Wayne water level gage showing surge and seiche for storm on Feb 27, 1997.

4.2.4 Convective storms

Several top 20 surges occurred during summer months and were likely associated with convective storms. Figure 43 shows an example time series of a convective storm surge event at Algonac and St. Clair Shores. However, the magnitude and frequency of the convective surges was small enough to produce no significant effect on the extremal distributions of still water level.

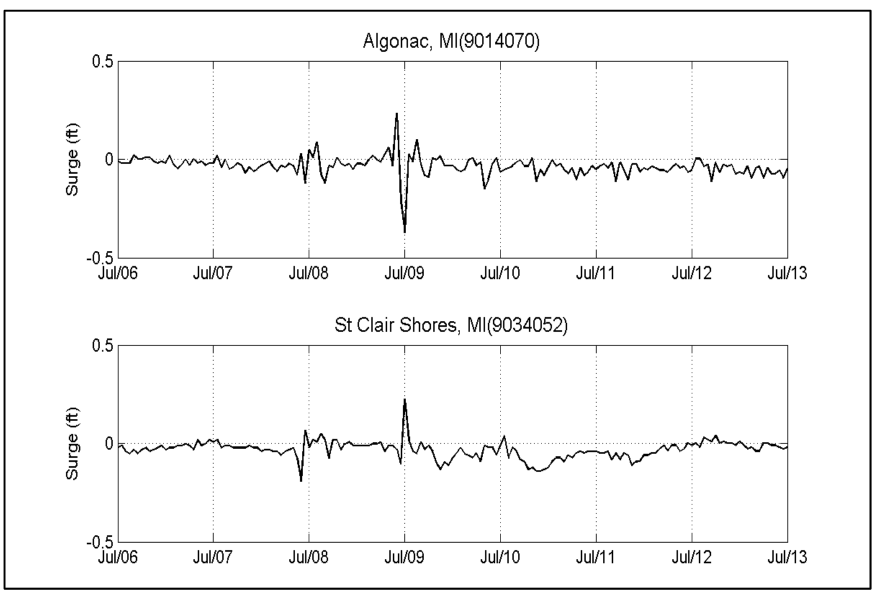

Figure 43. Surge measurements at Algonac and St. Clair Shores stations for convective storm on July 9, 1996.

4.3 Statistical correlation between storm surge and longer term water levels

In the previous FEMA Guidelines, the storm event water levels are assumed to have no correlation to the long term water levels. Figures 44 - 47 show correlations between event scale parameters and long term lake levels for each gage. Note that the surge was extracted from the measured water levels prior to the correlation analysis. No correlation of statistical significance was found between long-term water levels and storm events.

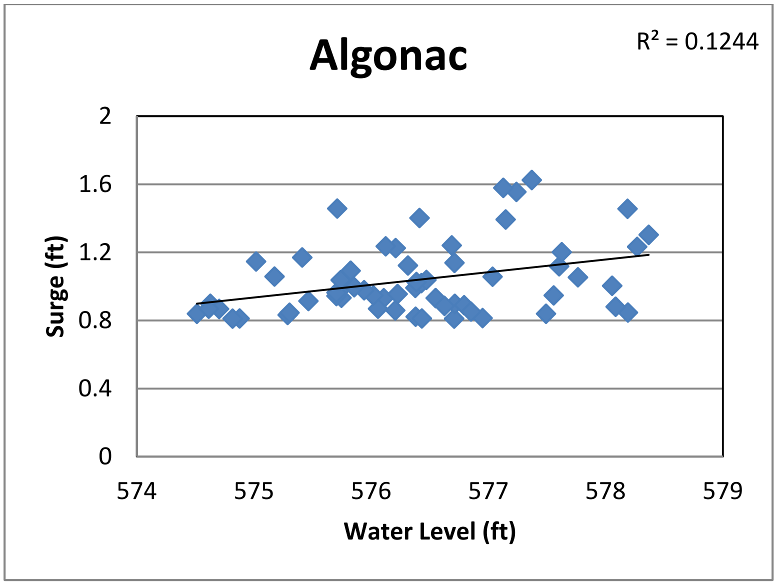

Figure 44. Correlation between surge and long term water levels for Algonac measurements.

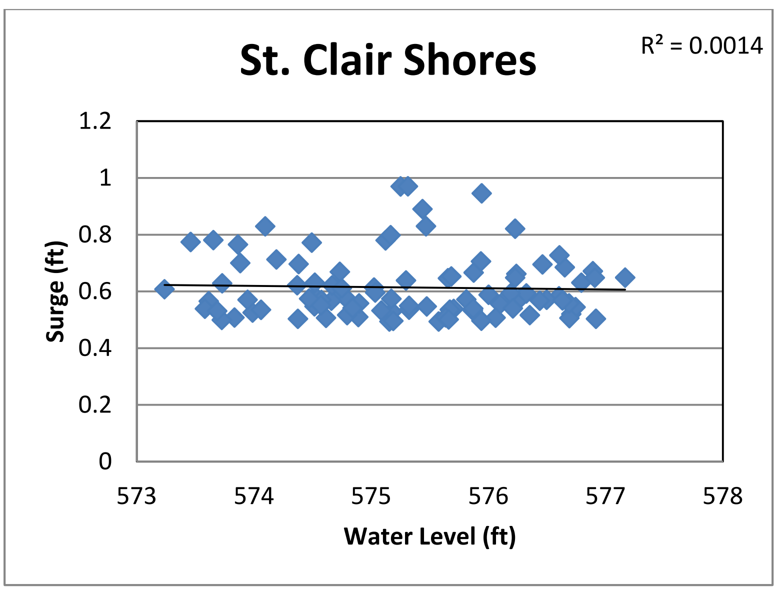

Figure 45. Correlation between surge and long term water levels for St. Clair Shores measurements.

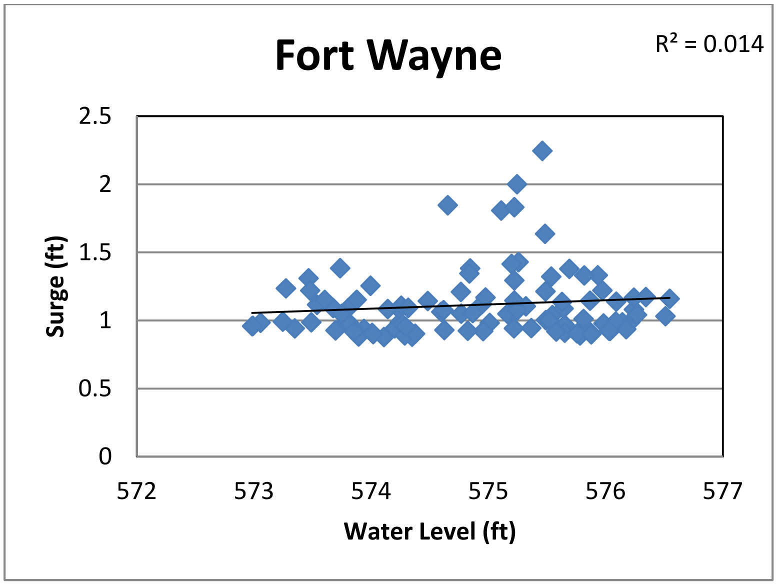

Figure 46. Correlation between surge and long term water levels for Fort Wayne measurements.

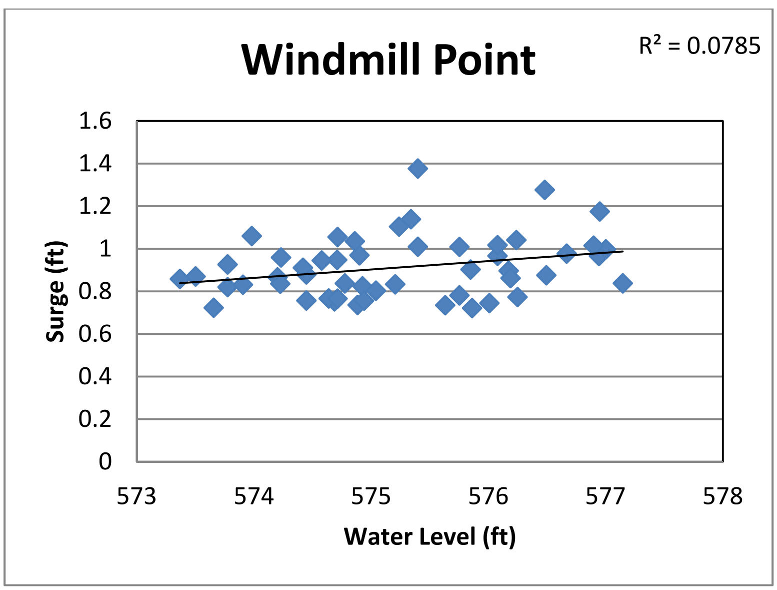

Figure 47. Correlation between surge and long term water levels for Windmill Point measurements.

5 Statistical Characteristics of Nearshore Water Levels for Lake Michigan

5.1 Analysis of extremes

A number of textbooks have been written on analysis of extreme values with particular emphasis on environmental variables (e.g. Coles 2001). For coastal applications a continuous times series is sampled to obtain a population of extreme values. Two types of samples can be produced: annual maximum series (AMS) or partial duration series (PDS). The most common partial duration series is obtained by selecting all peaks over a certain threshold, termed the peaks-over-threshold method (POT). In this method, only independent, identically distributed peaks are selected to avoid counting multiple peaks for a single storm as unique events. The AMS method simply uses the maximum event for each year over the duration of the data. Both methods are commonly used but the POT has begun to dominate in recent years because the method considers all extremes while the AMS method discards many significant storms.

For the Great Lakes, only AMS can be used to compute extreme probabilities selected directly from the total water level time series because the long term mean water level variations are of similar magnitude to event scale variations. In addition, lake levels do not conform to the requirement of independent, identically distributed events required for the POT analysis. However, for storm response parameters such as surge, wave height, and wind speed, either PDS or AMS can be used to describe the probabilistic nature of extremes. As was shown in previous chapters, it is common for intense storms to be clustered over several years and for this clustering to repeat on a decadal scale. This can be associated with El Niño/La Niña or similar decadal-scale climatic cycles. The result of this is that the AMS of storm responses will contain fewer of the most extreme events than the PDS. Therefore, the AMS will be less accurate in predicting higher return period values, particularly if the return period is greater than the duration of the statistical population. For that reason, the PDS is preferred for characterizing probabilistic behavior of extremal values of storm response.

5.2 Measured water levels

For measured water levels, the AMS were determined for all gages, the plotting position computed and the empirical distribution plotted for each water level station. Parametric distributions were fit using the method of moments. Candidate parametric distributions included General Extreme Value (GEV), Weibull, lognormal and generalized Pareto distribution (GPD). According to extreme value theory, the distribution of the AMS is the GEV distribution. The GEV becomes the Weibull distribution for maxima with an upper bound and the Fisher Tippett II distribution if bounded on the lower end. This distribution can also become the Gumbel or Fisher Tippett I under certain conditions.

The empirical and best-fit parametric distributions for AMS of measured water level are shown for two example Lake Michigan water level gages in Figures 48 - 49. For all sites, the GEV and log-normal distributions provided good fits while the Weibull and GPD produced poor fits. The GEV and log-normal fits were very similar and could be considered identical. The RMS_{25} value in the upper right corner of each plot is the root-mean-square (RMS) deviation between the fit and the empirical distribution for return periods of 25 years or more. Note that the distribution fits generally under-predict the water level of record. As described earlier, the actual exceedance probability of this event is dictated by the number of records and so its actual probability is unknown. Based on the extremal distributions of water level, the predicted one percent and 0.2 percent annual exceedance values are summarized in Table 13.

5.3 Storm surge

Storm surge values were computed as deviations of the measured water level time series from a moving average of the same time series. This moving average was generated using a Gaussian smoothing algorithm employing a 30-day time window.

Annual maximum series (AMS) and partial duration series (PDS) were each computed for the various wave and water level parameters discussed herein. In general, the focus is on the PDS for reasons stated above. The POT method was used to determine the PDS. The PDS values were rank ordered and the plotting positions calculated. Appendix A gives a general description of the methods. Generalized programs were developed to compute the marginal empirical distributions and fit parametric distributions using Matlab®.

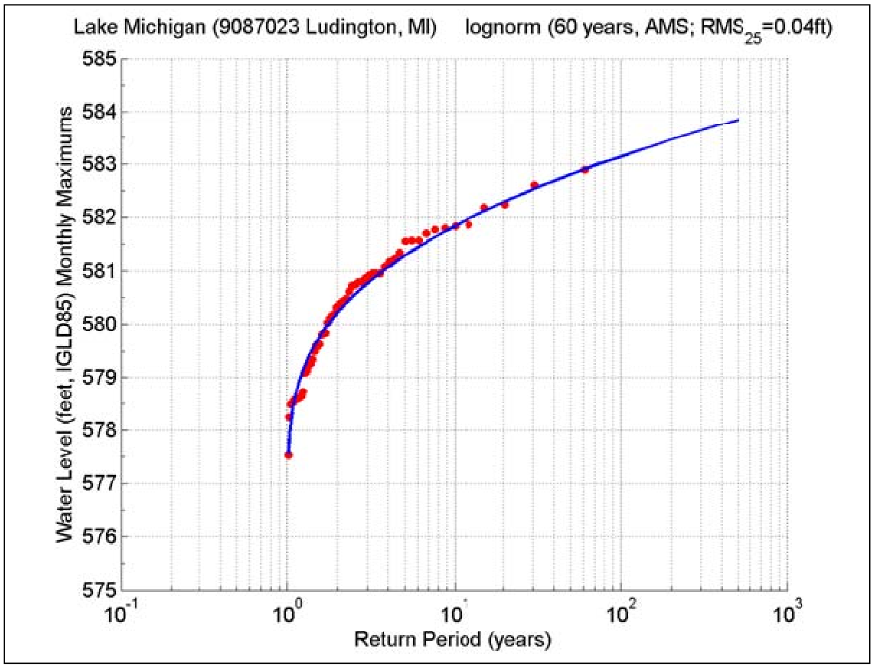

Figure 48. Ludington water level AMS empirical distribution and best-fit using log-normal distribution.

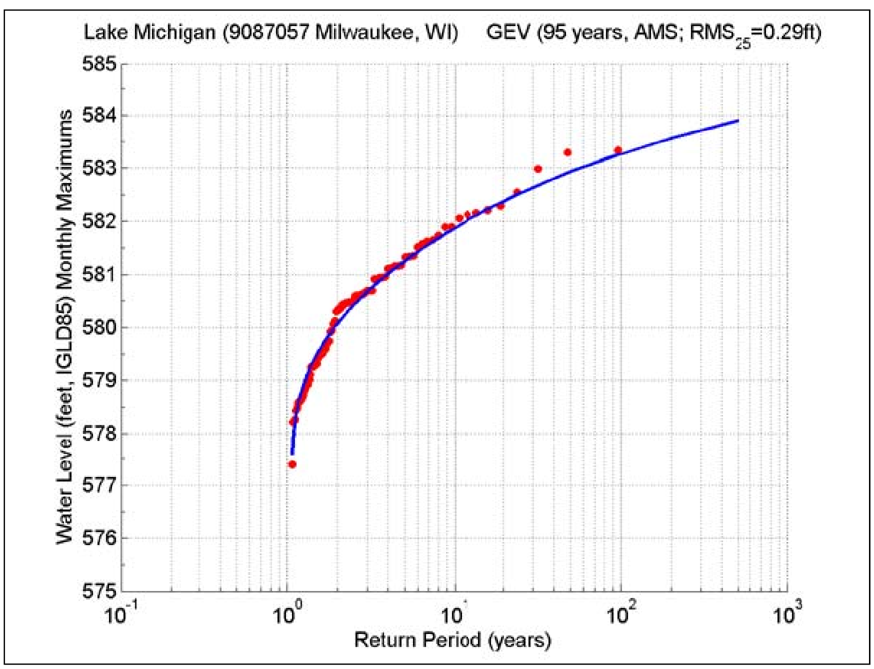

Figure 49. Milwaukee water level AMS empirical distribution and best-fit using GEV distribution.

Table 13. Water level statistics in ft, IGLD 1985.

Station	1 percent exceedance water level	0.2 percent exceedance water level
Mackinaw City	583.1	583.8
Ludington	583.2	583.5
Holland	583.3	584.0
Calumet	583.8	584.3
Milwaukee	583.3	583.8
Kewaunee	582.8	583.0
Sturgeon Bay	583.5	584.3
Green Bay	584.5	585.2
Port Inland	584.0	584.8

5.3.1 Surge distributions

The top 20 PDS storm surge values are listed for each gage in Tables 14 - 22. Figure 50 shows the top 20 PDS values for the north lake stations while Figure 51 shows the south lake stations. Central lake stations Kewaunee and Ludington are on both plots. It is clear that the peaks are distributed over the entire gage records except for early Calumet, with only one peak prior to 1939. However, surges appear to be grouped during specific time periods. Also, Calumet, Port Inland and Green Bay have significantly higher maximum surge values than the other stations reflecting their exposure to greater fetch lengths. For Calumet, Port Inland and Green Bay, the maximum surges are between 3.5 and 5.4 ft. For the other stations, the maximum surges are between 1.5 and 2.5 ft.

Figures 52 – 54 show correlations for storm surge between gages using hourly water levels from 1970 to 2009. The correlations were computed for each PDS value by searching all the other gage records for a peak within a 4 day period surrounding each PDS time. That way, the impact of each storm on all gages is considered including changing wind direction and seiches. The correlations are quite low even for gages that are relatively close together and there is no correlation between gages that are separated by at least half the lake length. This is important in determining whether a given gage record can be used at other locations.

Table 14. Top 20 surge events ranked from highest to lowest from peaks-over-threshold analysis of Mackinaw City water level gage data.

Rank	Date	Surge (ft)
1	11/20/1985	2.01
2	12/15/1948	1.85
3	11/15/1940	1.67
4	11/15/1931	1.61
5	11/15/1946	1.56
6	3/15/1939	1.50
7	11/10/1975	1.49
8	11/10/1998	1.47
9	10/15/1951	1.42
10	11/16/1988	1.40
11	11/15/1957	1.38
12	9/15/1924	1.38
13	11/15/1955	1.36
14	1/15/1960	1.35
15	11/15/1919	1.34
16	12/23/2007	1.33
17	9/24/1985	1.33
18	9/15/1959	1.31
19	1/11/1975	1.30
20	12/15/1943	1.30

Table 15. Top 20 surge events ranked from highest to lowest from peaks-over-threshold analysis of Ludington water level gage data.

Rank	Date	Surge (ft)
1	2/15/1964	1.51
2	1/15/1969	1.49
3	3/5/1985	1.32
4	4/15/1966	1.30
5	1/23/1982	1.29
6	4/3/1982	1.29
7	11/15/1965	1.27
8	11/2/1992	1.25

Rank	Date	Surge (ft)
9	11/15/1952	1.25
10	11/28/1994	1.17
11	12/15/1950	1.17
12	10/1/1981	1.15
13	1/15/1967	1.15
14	11/15/1955	1.14
15	12/15/1966	1.13
16	11/15/1960	1.12
17	4/15/1960	1.12
18	12/15/1971	1.12
19	1/15/1952	1.11
20	3/15/1956	1.11

Table 16. Top 20 surge events ranked from highest to lowest from peaks-over-threshold analysis of Holland water level gage data.

Rank	Date	Surge (ft)
1	12/4/1990	2.01
2	12/2/1985	1.75
3	12/30/1971	1.58
4	4/4/1982	1.55
5	1/4/1982	1.47
6	1/26/1971	1.45
7	11/15/1961	1.43
8	2/15/1967	1.42
9	12/15/1968	1.36
10	12/9/2009	1.36
11	4/15/1963	1.35
12	3/10/2002	1.25
13	1/25/1990	1.25
14	12/16/1987	1.25
15	12/4/1970	1.22
16	4/15/1966	1.20
17	1/25/1972	1.20
18	3/15/1964	1.19
19	12/15/1966	1.16
20	11/13/2003	1.12

Table 17. Top 20 surge events ranked from highest to lowest from peaks-over-threshold analysis of Calumet water level gage data.

Rank	Date	Surge (ft)
1	10/15/1929	3.50
2	12/15/1965	3.31
3	3/15/1960	3.25
4	9/23/1989	3.06
5	5/31/1998	2.82
6	1/15/1947	2.70
7	3/9/1998	2.60
8	12/29/1998	2.57
9	4/15/1946	2.45
10	11/15/1950	2.44
11	5/15/1947	2.43
12	1/15/1948	2.35
13	11/15/1966	2.33
14	12/26/1989	2.33
15	7/15/1954	2.27
16	10/15/1939	2.20
17	2/8/1987	2.20
18	12/15/1948	2.20
19	12/15/1968	2.18
20	10/1/1994	2.17

Table 18. Top 20 surge events ranked from highest to lowest from peaks-over-threshold analysis of Milwaukee water level gage data.

Rank	Date	Surge (ft)
1	3/15/1954	2.17
2	3/9/1987	2.13
3	1/15/1922	1.98
4	12/15/1987	1.95
5	10/15/1929	1.87
6	3/15/1917	1.81
7	12/3/1990	1.78
8	5/15/1927	1.74
9	5/15/1918	1.65
10	6/15/1918	1.63

Rank	Date	Surge (ft)
11	3/4/1985	1.61
12	6/15/1917	1.59
13	12/15/1965	1.56
14	3/9/1998	1.53
15	12/15/1968	1.53
16	12/30/1971	1.52
17	5/15/1923	1.50
18	3/15/1929	1.42
19	6/15/1924	1.41
20	2/8/1987	1.41

Table 19. Top 20 surge events ranked from highest to lowest from peaks-over-threshold analysis of Kewaunee water level gage data.

Rank	Date	Surge (ft)
1	9/4/1990	2.45
2	6/2/1995	1.99
3	8/4/2002	1.95
4	11/2/1992	1.52
5	10/15/1973	1.47
6	4/15/1996	1.29
7	3/4/1985	1.26
8	11/28/1994	1.26
9	12/20/1978	1.22
10	10/28/1973	1.22
11	4/12/1979	1.17
12	9/22/1980	1.14
13	4/12/1995	1.14
14	11/23/2003	1.14
15	12/23/2007	1.13
16	3/2/2007	1.11
17	4/12/2001	1.09
18	3/31/1985	1.08
19	5/21/2004	1.07
20	11/2/1991	1.04

Table 20. Top 20 surge events ranked from highest to lowest from peaks-over-threshold analysis of Sturgeon Bay Canal water level gage data.

Rank	Date	Surge (ft)
1	2/15/1962	2.46
2	5/15/1953	2.25
3	3/15/1954	2.14
4	6/29/1996	2.00
5	9/23/1997	2.00
6	7/22/1993	1.98
7	7/11/1996	1.84
8	12/15/1950	1.68
9	11/15/1956	1.68
10	12/15/1955	1.56
11	3/15/1952	1.50
12	11/2/1992	1.48
13	11/15/1957	1.40
14	11/15/1952	1.38
15	3/15/1963	1.37
16	11/15/1955	1.36
17	5/15/1964	1.35
18	3/4/1985	1.34
19	3/15/1966	1.29
20	11/15/1965	1.28

Table 21. Top 20 surge events ranked from highest to lowest from peaks-over-threshold analysis of Green Bay water level gage data.

Rank	Date	Surge (ft)
1	12/3/1990	5.41
2	12/9/2009	3.98
3	12/15/1965	3.76
4	4/16/1993	3.49
5	4/9/1973	3.34
6	4/15/1961	3.14
7	4/15/1963	3.11
8	11/3/1970	3.09

Rank	Date	Surge (ft)
9	4/20/2000	2.99
10	4/20/1993	2.85
11	9/15/1963	2.83
12	9/15/1959	2.77
13	10/23/1972	2.72
14	11/5/1993	2.65
15	5/15/1963	2.64
16	10/15/1959	2.62
17	11/15/1956	2.59
18	12/15/1987	2.58
19	4/12/2007	2.57
20	10/15/1969	2.56

Table 22. Top 20 surge events ranked from highest to lowest from peaks-over-threshold analysis of Port Inland water level gage data.

Rank	Date	Surge (ft)
1	1/11/1975	3.67
2	11/11/1998	2.83
3	11/20/1985	2.43
4	11/16/2005	2.36
5	11/15/1965	2.10
6	11/28/1994	2.05
7	5/15/1966	2.04
8	11/16/1988	1.97
9	1/23/1982	1.95
10	12/23/2007	1.90
11	11/24/1983	1.89
12	10/15/1967	1.80
13	11/2/1991	1.78
14	3/5/1985	1.67
15	11/10/1975	1.64
16	3/15/1966	1.62
17	6/15/1969	1.62
18	11/2/1992	1.57
19	2/5/1971	1.56
20	6/15/1966	1.55

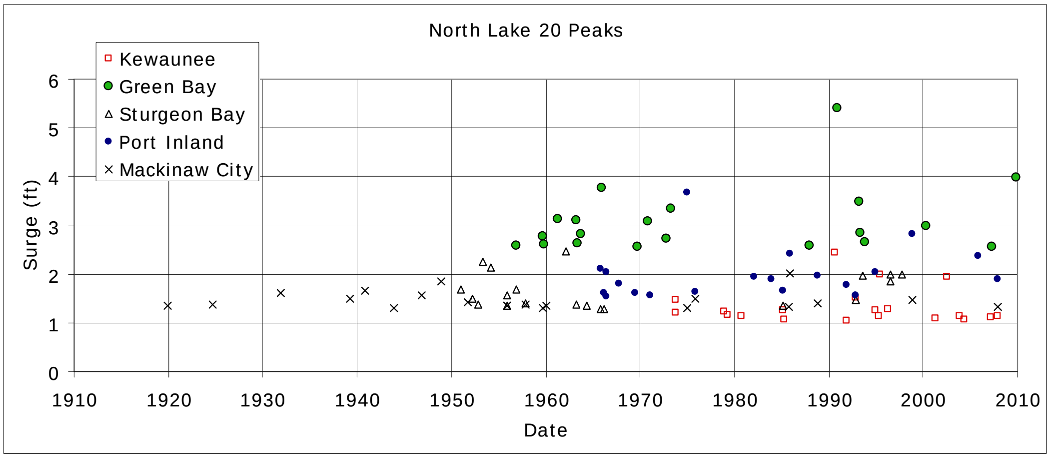

Figure 50. Top 20 events ranked by surge for north lake water level gages.

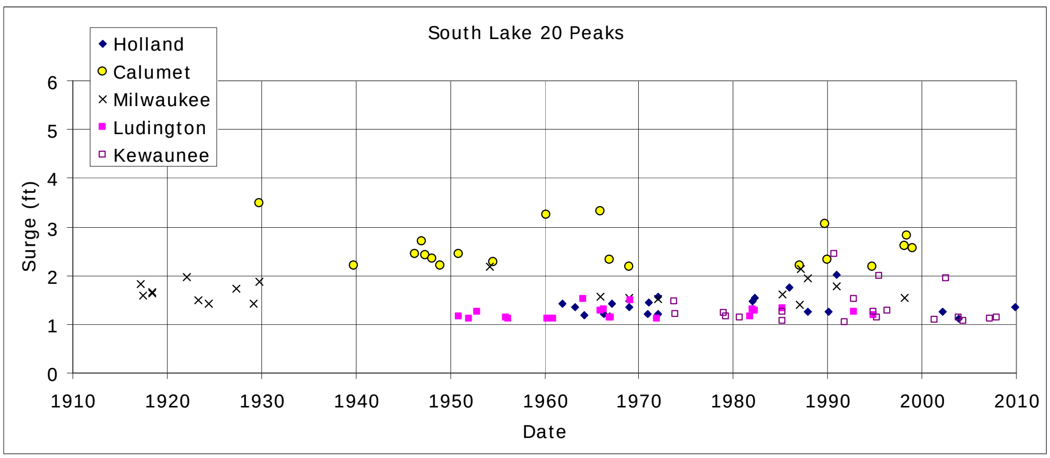

Figure 51. Top 20 events ranked by surge for south lake water level gages.

Figures 55 - 62 show how the PDS surge values vary with month of the year in both frequency and magnitude. Some stations show no significant surge events during the summer months (Ludington, Holland) while others show significant summer peak surge values. Note that the Mackinaw City gage data was not considered in this analysis.

5.3.2 Length of record impacts

Length of record of water levels or surge levels dictates the AEP of each storm and therefore the BFE. In the POT technique, selecting a higher λ value gives more storms from a given record length (see Appendix A). This has little impact on the BFE. However, a longer historical record has significant impact on the accuracy of the extremal analysis. Figure 63 shows empirical extremal distributions of storm surge for Calumet with four different curves representing four different record lengths. The curves are as follows:

- 2010: record length of 108 yrs for period 1/1902 – 1/2010
- 2001: record length of 99 yrs for period 1/1902 – 1/2001
- 1994: record length of 92 yrs for period 1/1902 – 1/1994
- 1980: record length of 78 yrs for period 1/1902 – 1/1980

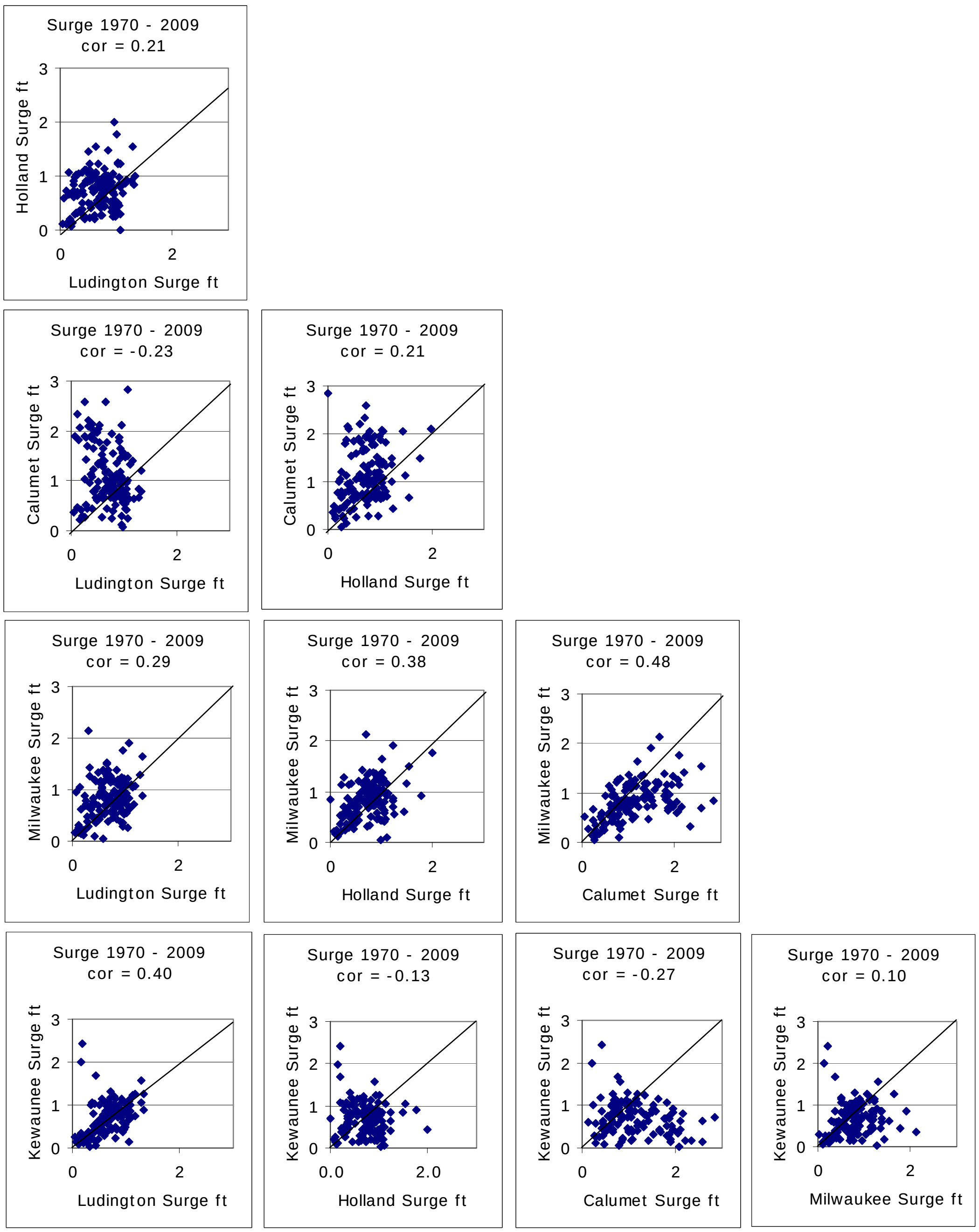

Figure 52. Measured surge correlations between gages.

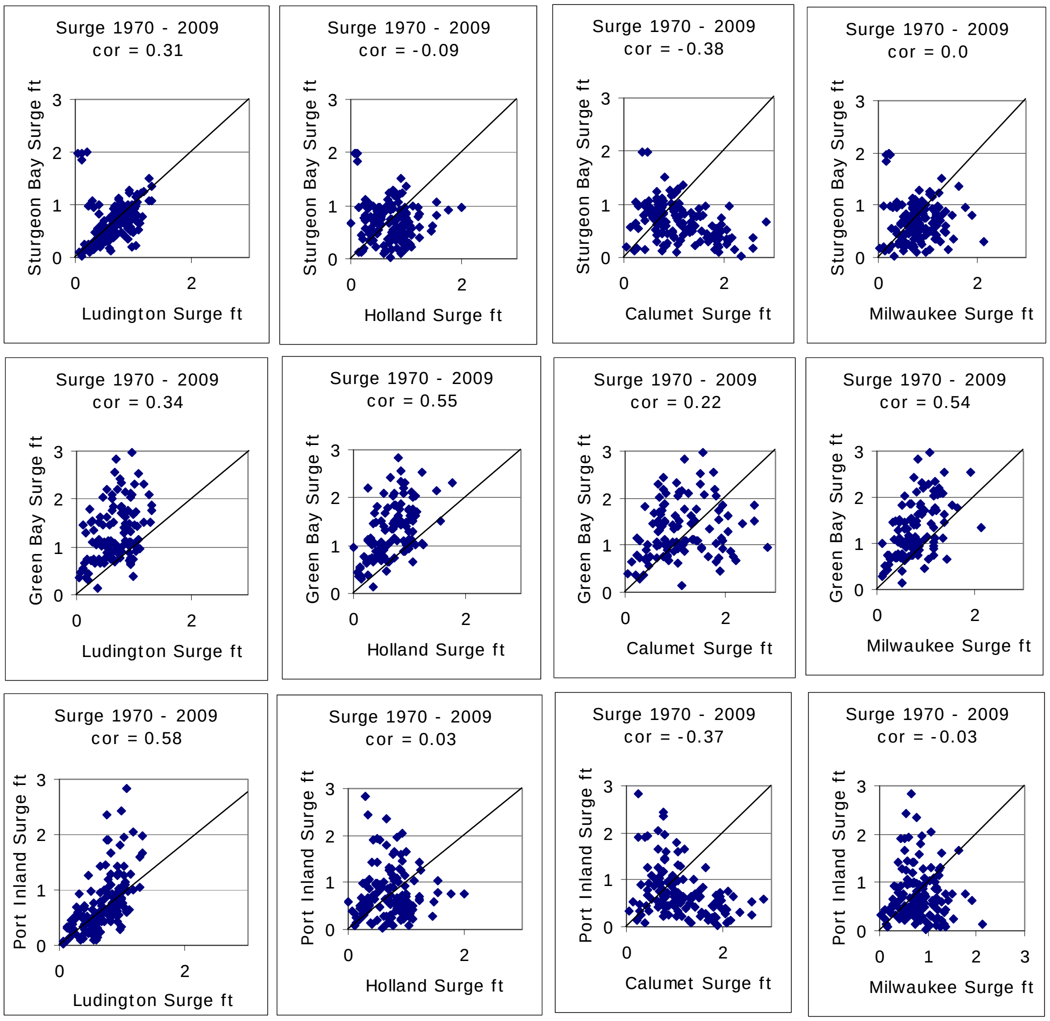

Figure 53. Measured surge correlations between gages.

The figure is fairly typical of extremal surge distributions and shows clearly the impact of record length. For short record lengths, the extremal distribution is too steep and crosses the more accurate distributions that are based on longer record lengths. At some point, the record length becomes sufficiently long so that additional years do not change the overall shape. However, increasing record length will continue to move the distribution down and to the right. In most cases, a shorter record length will yield a more conservative estimate of the BFE than a longer record length. However, if the record length is too short, then the extremal distribution will be too steep resulting in a significant over-prediction of the BFE, in some cases.

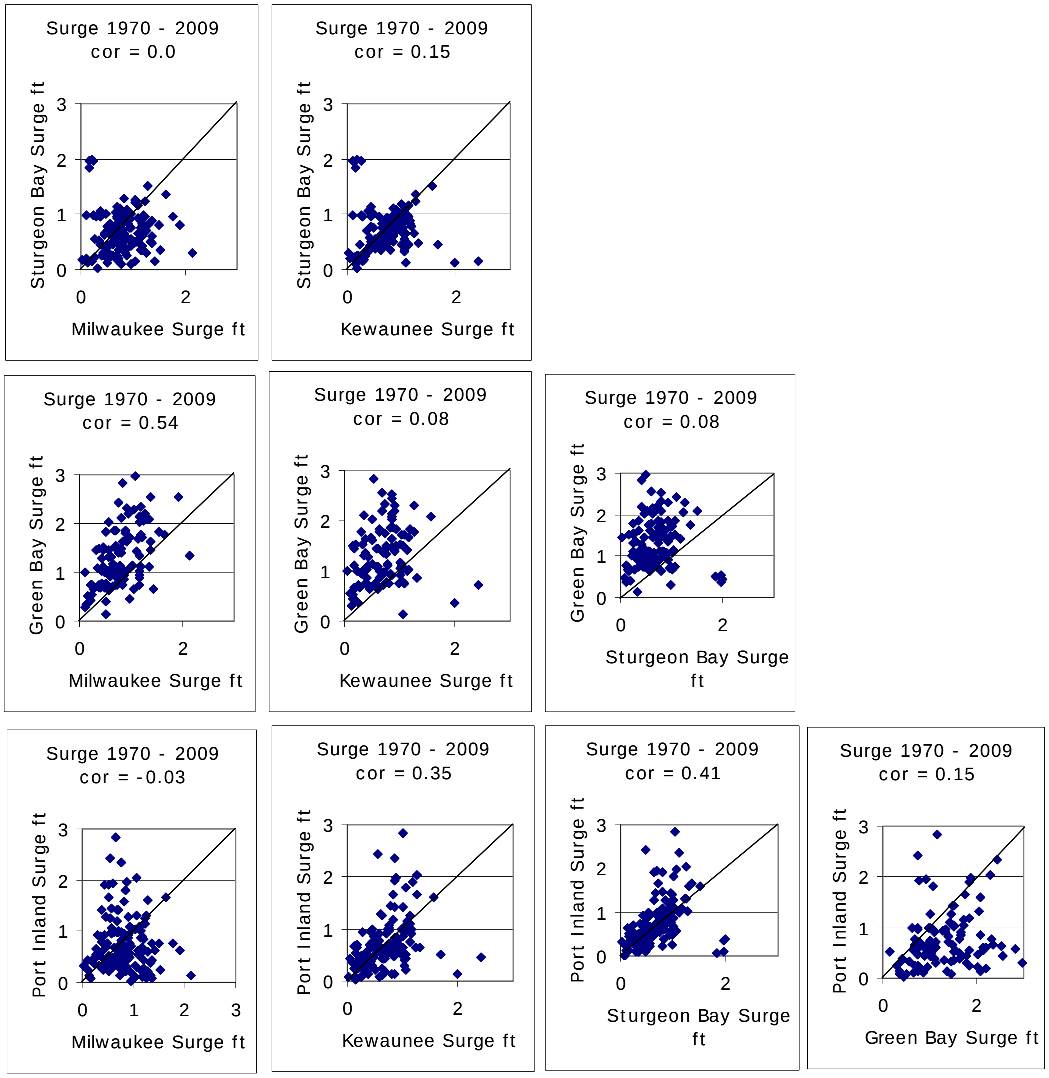

Figure 54. Measured surge correlations between gages.

As another example, Figure 64 shows a similar plot for Kewaunee. Here the record length is only 38 years for the longest record. It is clear that the record length is not long enough and the more realistic extremal distribution is probably flatter. Unfortunately, the real distribution is unknown due to insufficient data.

Figure 65 shows a similar plot of empirical surge distributions for Sturgeon Bay. In this case, the longest record length is 61 years and appears to be a reasonable representation of the extremal distribution. The shortest record length that still gives the same shape is the 2001 curve which represents a record length of 52 years.

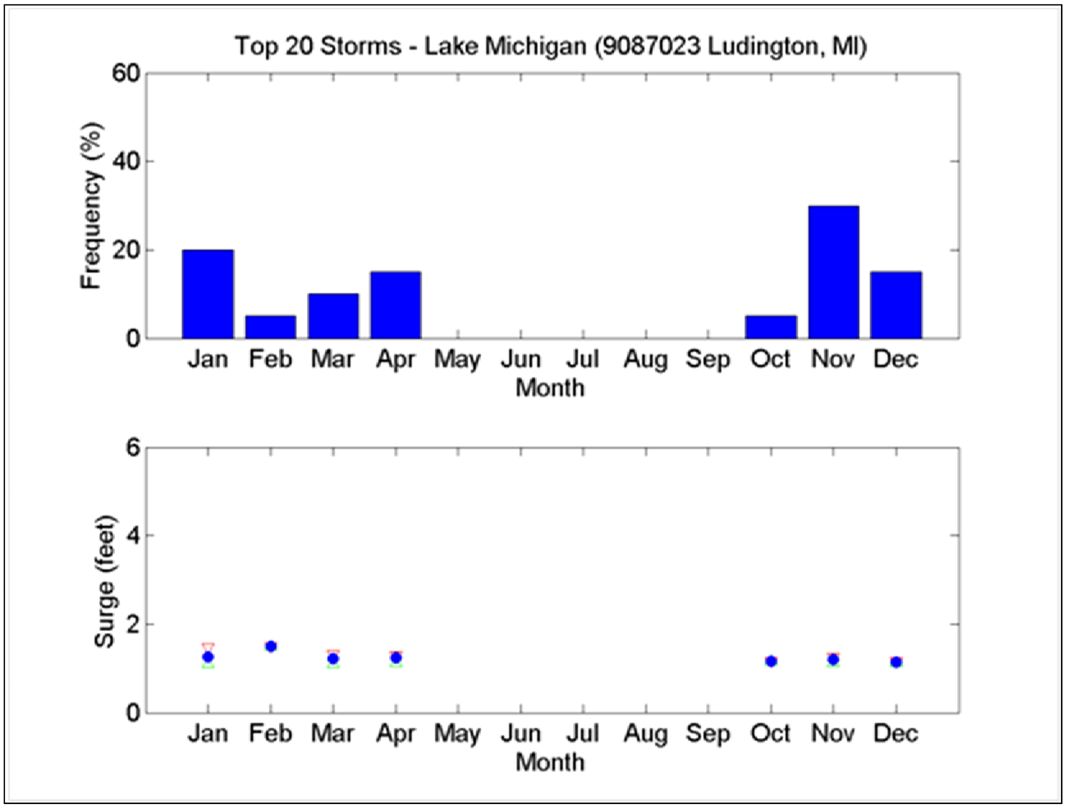

Figure 55. PDS surge values by month for Ludington gage.

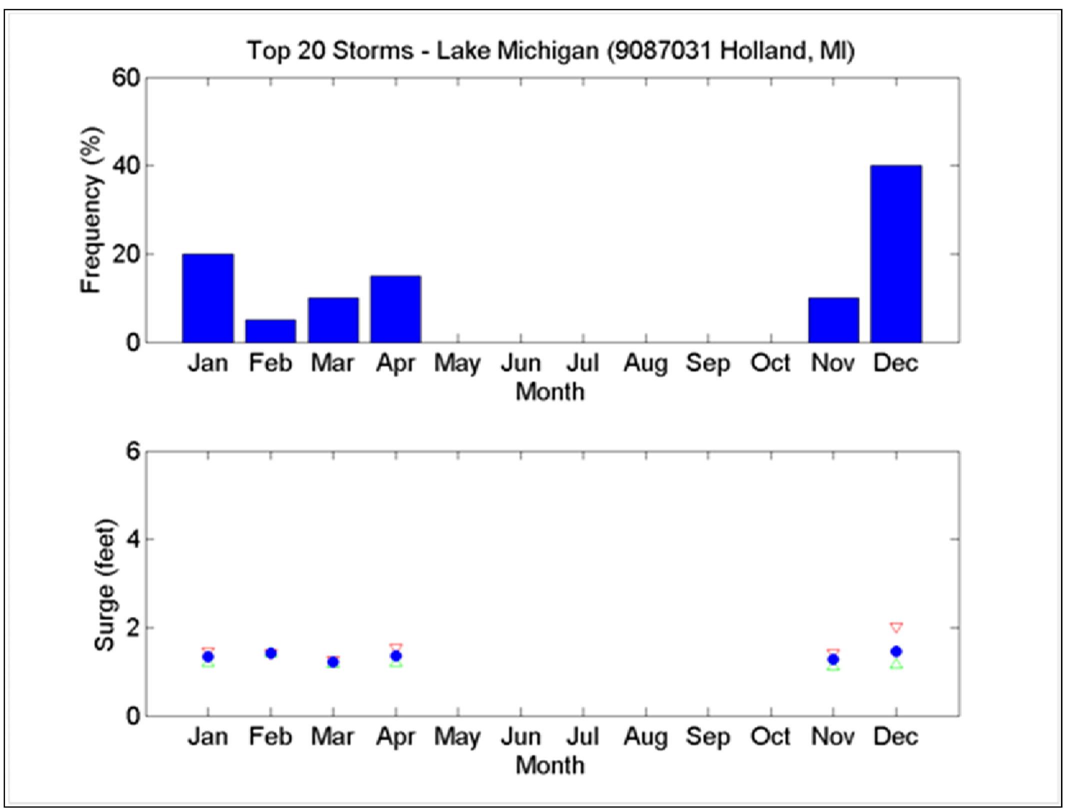

Figure 56. PDS surge values by month for Holland gage.

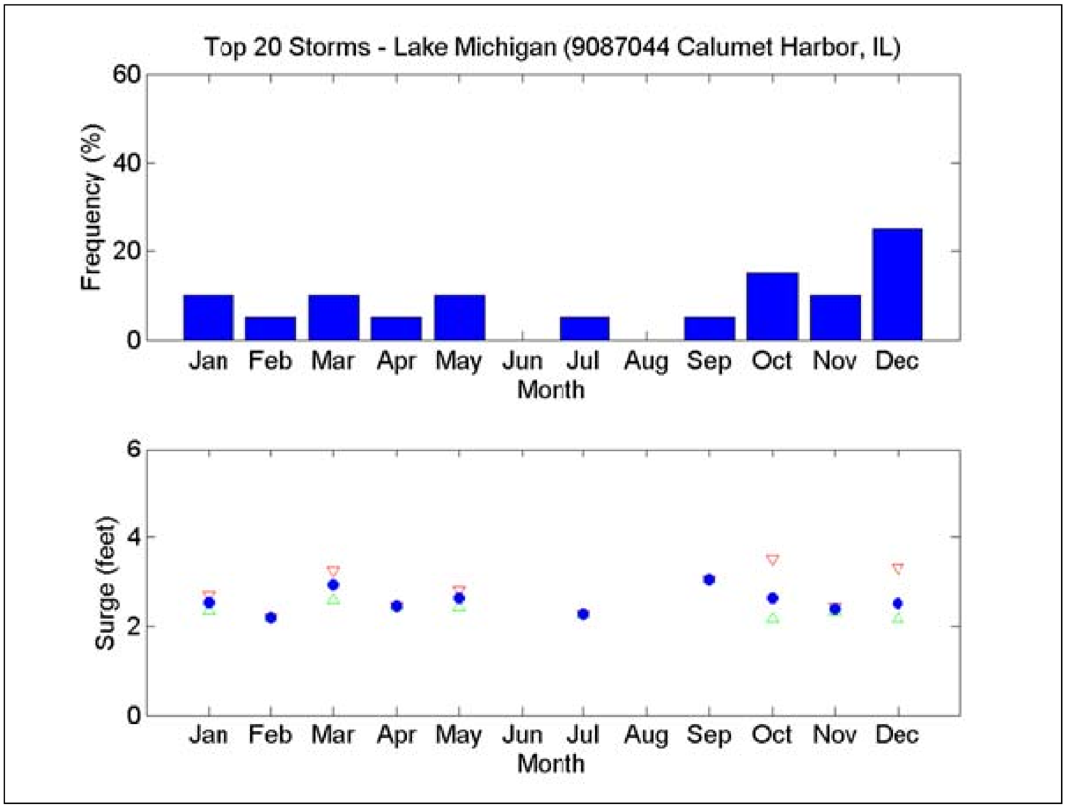

Figure 57. PDS surge values by month for Calumet gage.

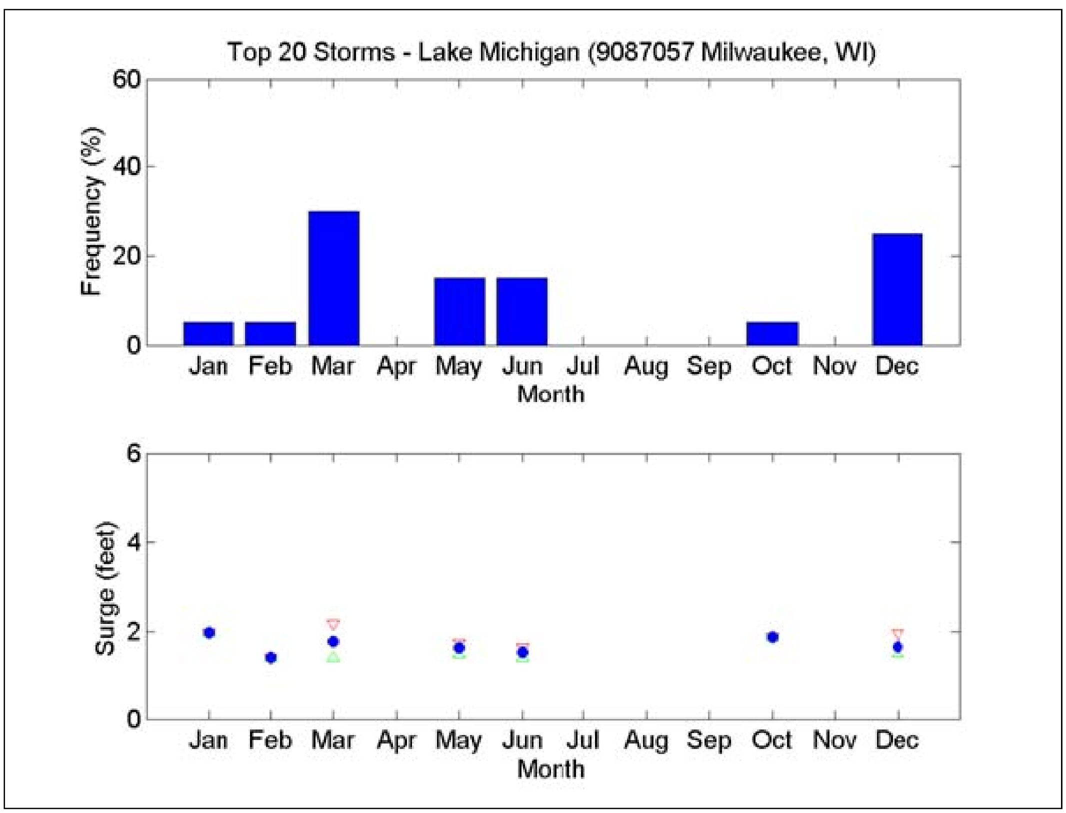

Figure 58. PDS surge values by month for Milwaukee gage.

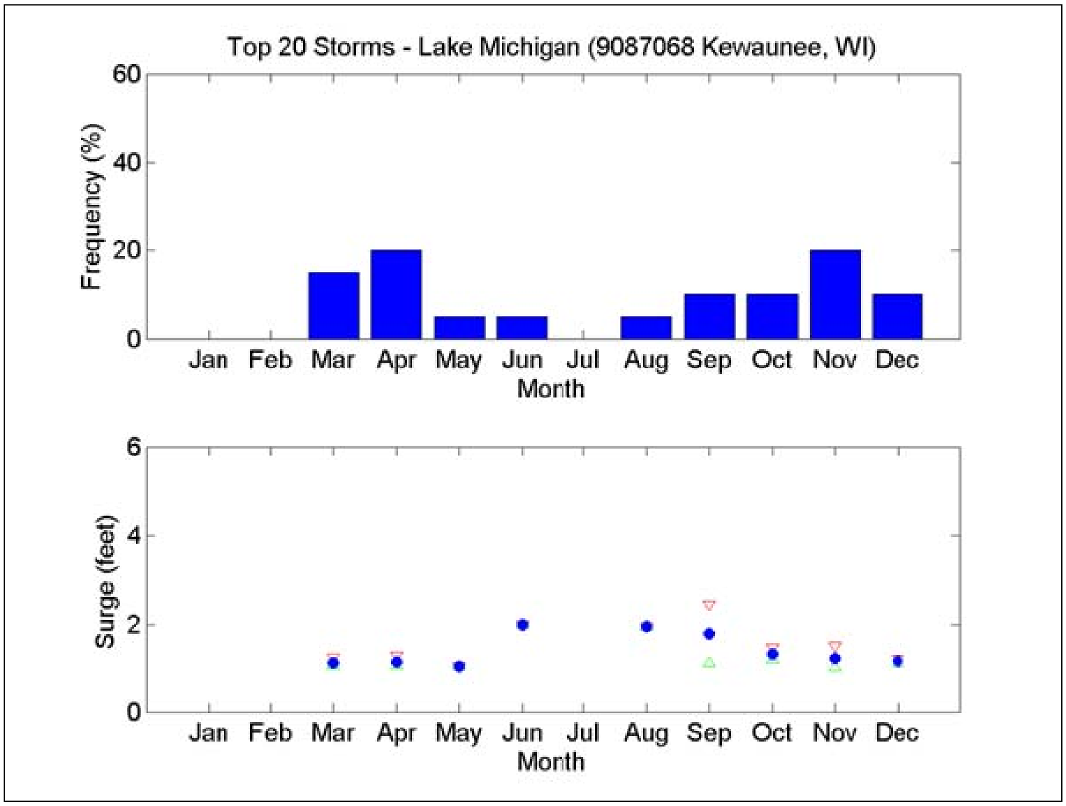

Figure 59. PDS surge values by month for Kewaunee gage.

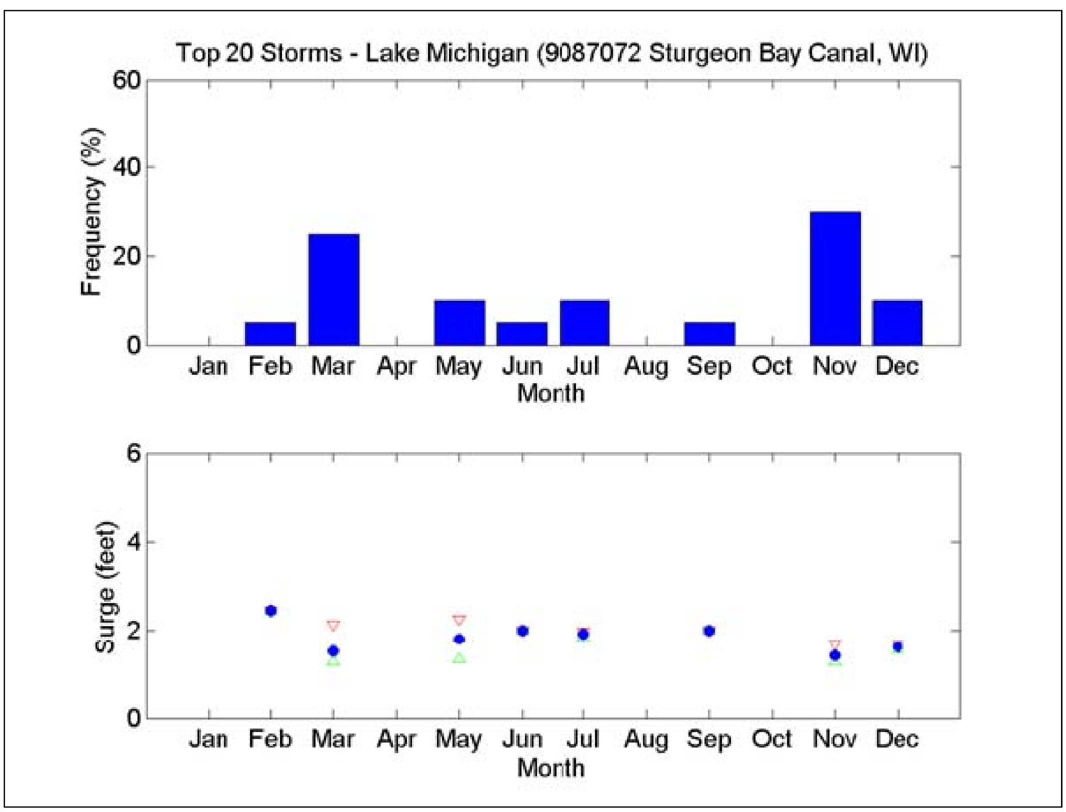

Figure 60. PDS surge values by month for Sturgeon Bay gage.

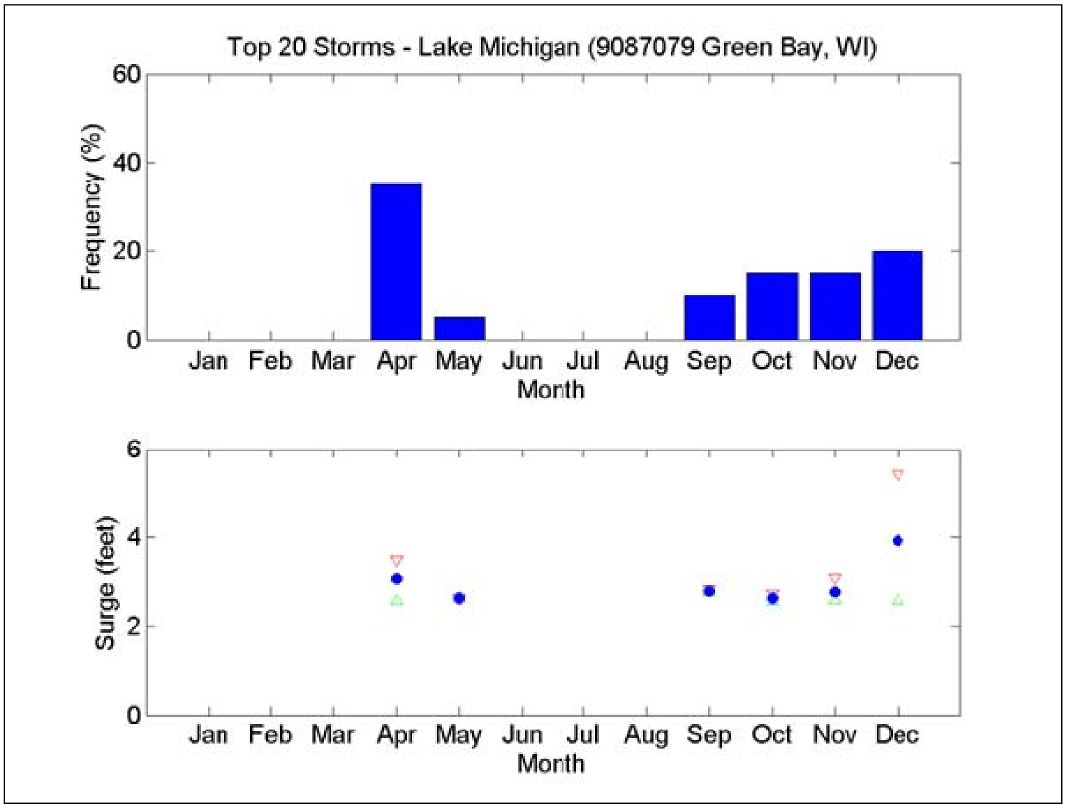

Figure 61. PDS surge values by month for Green Bay gage.

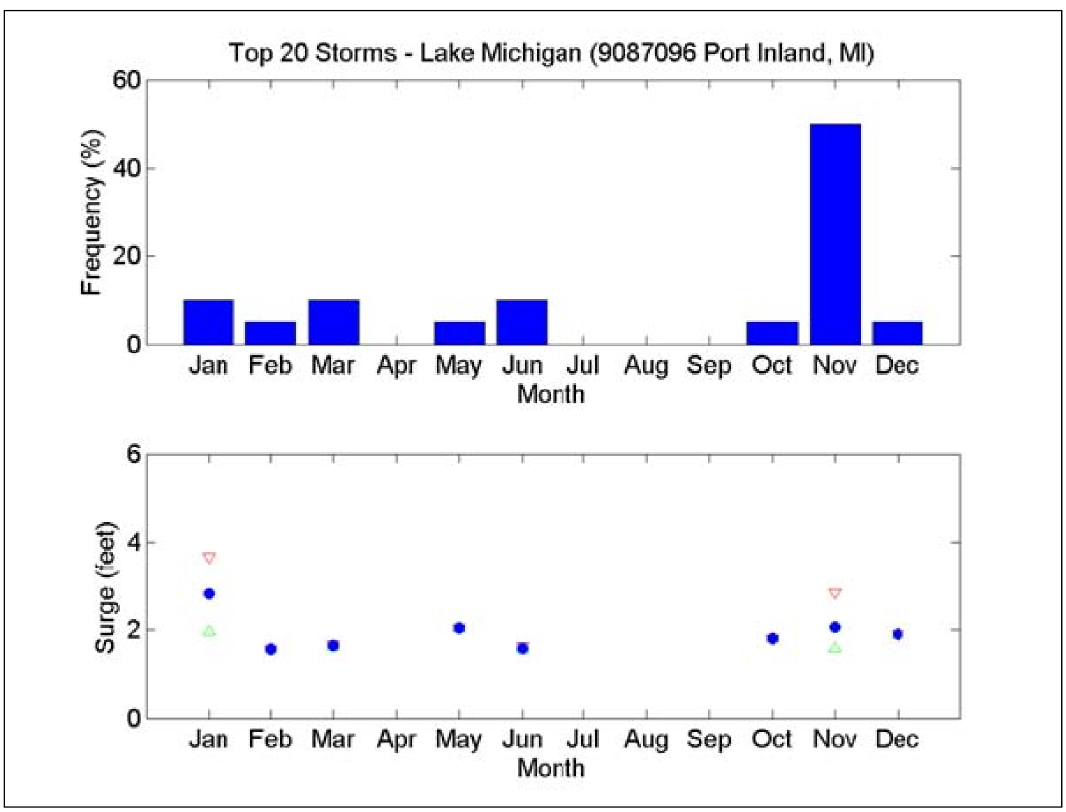

Figure 62. PDS surge values by month for Port Inland gage.

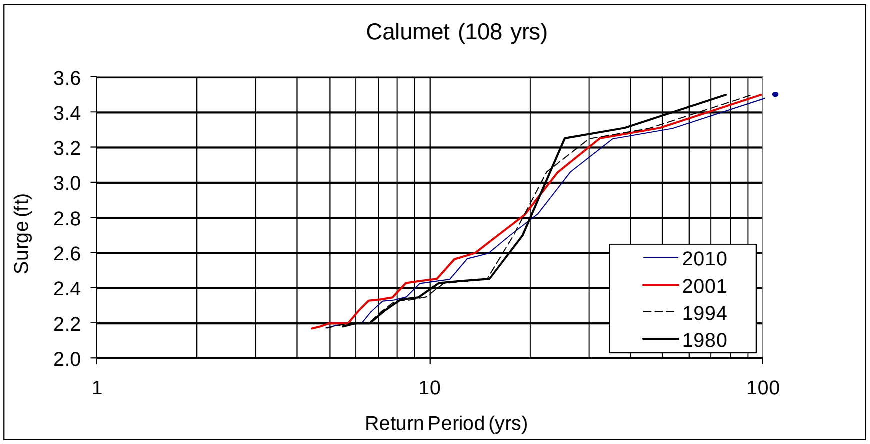

Figure 63. Empirical extremal distribution of measured surge for varying record lengths for Calumet gage.

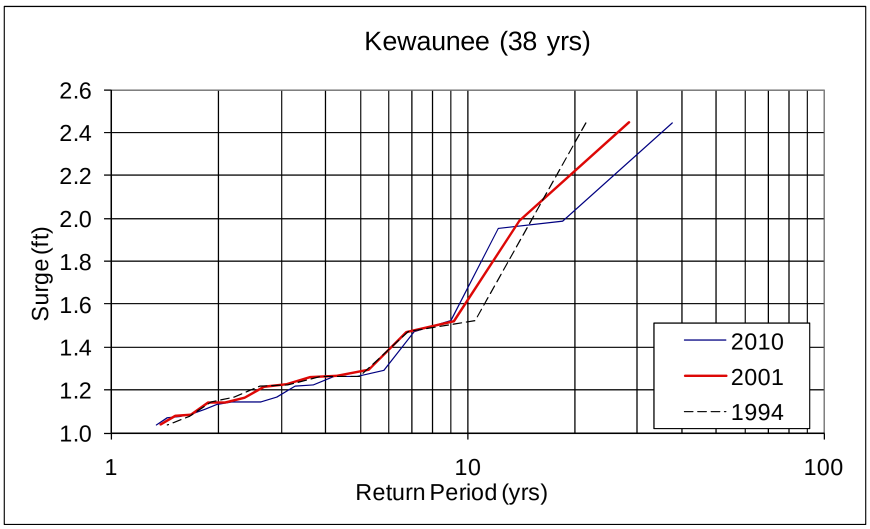

Figure 64. Kewaunee empirical extremal curves for varying record lengths.

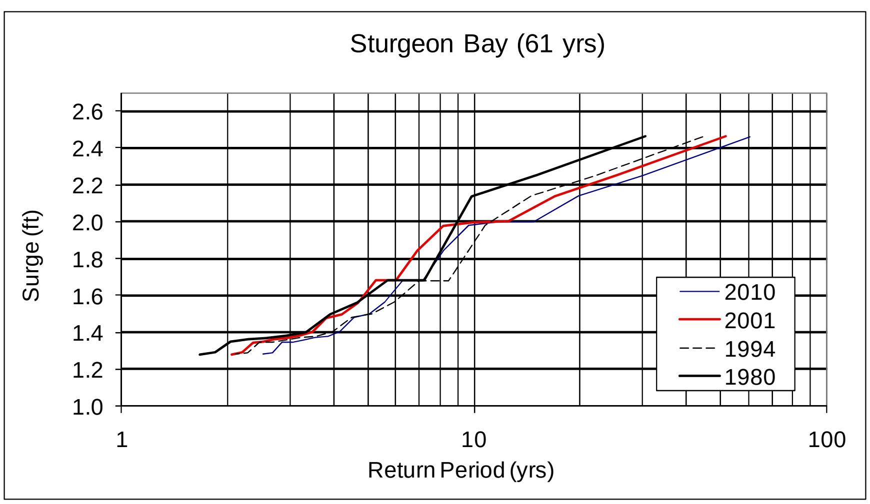

Figure 65. Sturgeon Bay empirical extremal curves for varying record lengths.

Table 23 lists all of the gages, the total record length, the duration that gives the correct shape of the extremal distribution, and the percent difference between the 100-yr return period surge for the minimum acceptable record length and that for the total record length. The N/A values indicate that the distributions were likely not accurate due to too few years in the record. The record lengths were simply not long enough to definitively say whether the distributions would change significantly with a longer record length. The low values in the percent difference column suggest that there is only a slight improvement in adding an additional 10 to 15 years to the record length as long as the basic shape of actual extremal distribution is captured. This analysis suggested that the minimum acceptable record length was 50 years for the study.

Table 23. Record lengths required to achieve correct distribution shape and percent difference between the 100-yr return period surge for the minimum acceptable record length and that for the total record length.

Station	Record Length, yrs	Correct Shape Duration, yrs	Percent Difference
Mackinaw City	96	80	3
Ludington	61	45	0.5
Holland	52	52	N/A
Calumet	108	99	0.6
Milwaukee	96	87	0.5
Kewaunee	38	38	N/A
Sturgeon Bay	61	52	1.9
Green Bay	57	57	N/A
Port Inland	46	46	N/A

5.3.3 Parametric probability distributions of storm surge

Empirical and best-fit parametric extremal distributions from the POT analysis of storm surge are shown in Figures 66 – 68 for Ludington, Milwaukee, and Green Bay gages, as examples. Extreme value theory tells us that the PDS determined from the POT method should conform to the generalized Pareto distribution (GPD). The GPD was fit using the method of moments. In this case $\lambda = 10$. For most fits, there appears to be a different statistical family starting at a return period of roughly 10 years. A better fit could be obtained by using a second distribution to fit points above this return period. However, fitting a second distribution to the few extreme points would require using hand fitting because there are too few points to apply one of the objective analytical fitting techniques. The critical issue

with surge distributions is the probability of the most extreme values because they are dictated by the record length. So, as stated previously, the probability of the most extreme values is unknown.

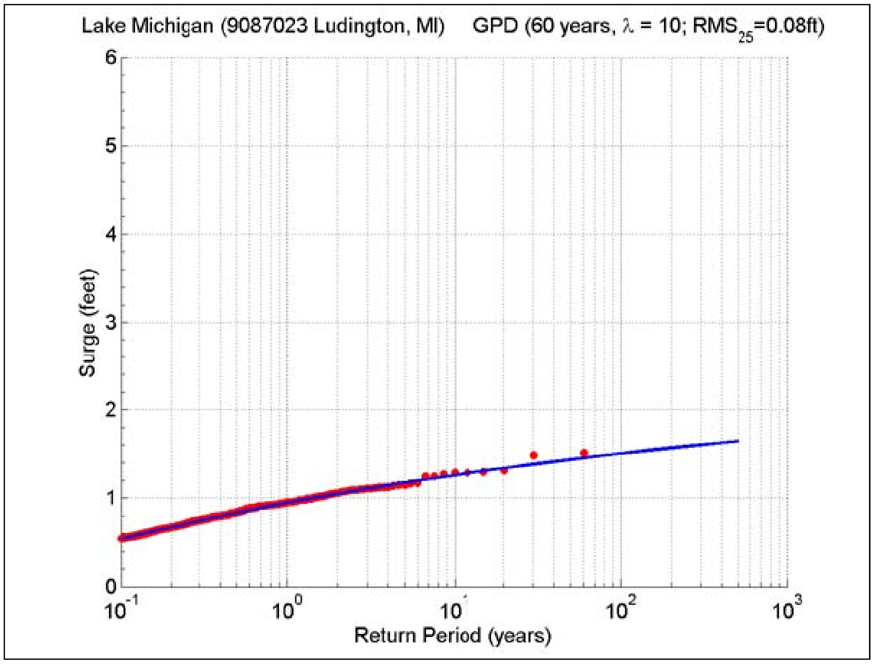

Figure 66. Ludington surge PDS empirical distribution and best fit using GPD.

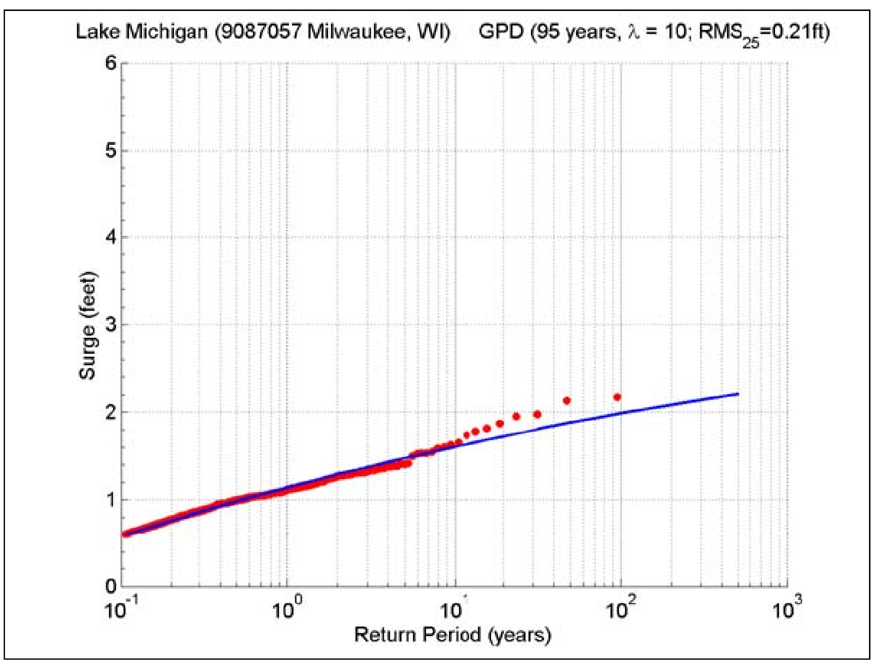

Figure 67. Milwaukee surge PDS empirical distribution and best fit using GPD.

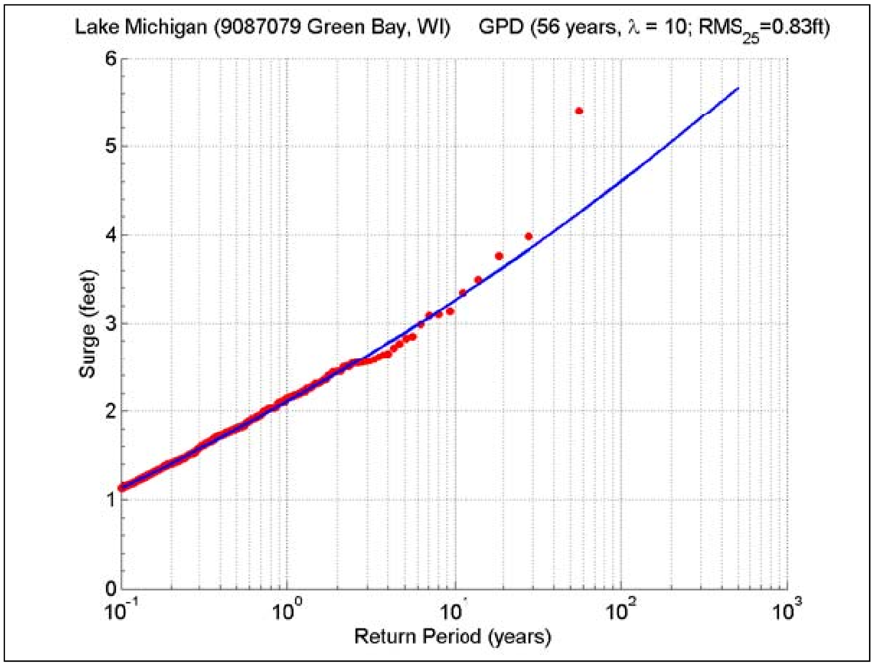

Figure 68. Green Bay surge PDS empirical distribution and best fit using GPD.

5.4 WIS wave heights

The WIS wave height extreme values at WIS stations nearest each water level gage were also analyzed. The WIS data are used herein as a surrogate for offshore waves to validate the FIS methodology and screen for storms to be modeled in the production modeling phase.

For the WIS hindcasts, the PDS was computed using the POT method as previously described. Figures 69 – 71 show the empirical distributions as well as the best-fit parametric probability distributions for Ludington, Milwaukee, and Green Bay, as examples. In general, the GPD provided the best fit.

5.5 Total water level including runup

As stated previously, the BFE will likely not be sufficiently accurate if gage values are spatially interpolated because there is little correlation between gages. The record length must be sufficiently long to capture the correct shape of the extremal distribution of water levels. Based on the preceding discussion, 50 years is the minimum duration required to achieve the correct total water level distribution shape.

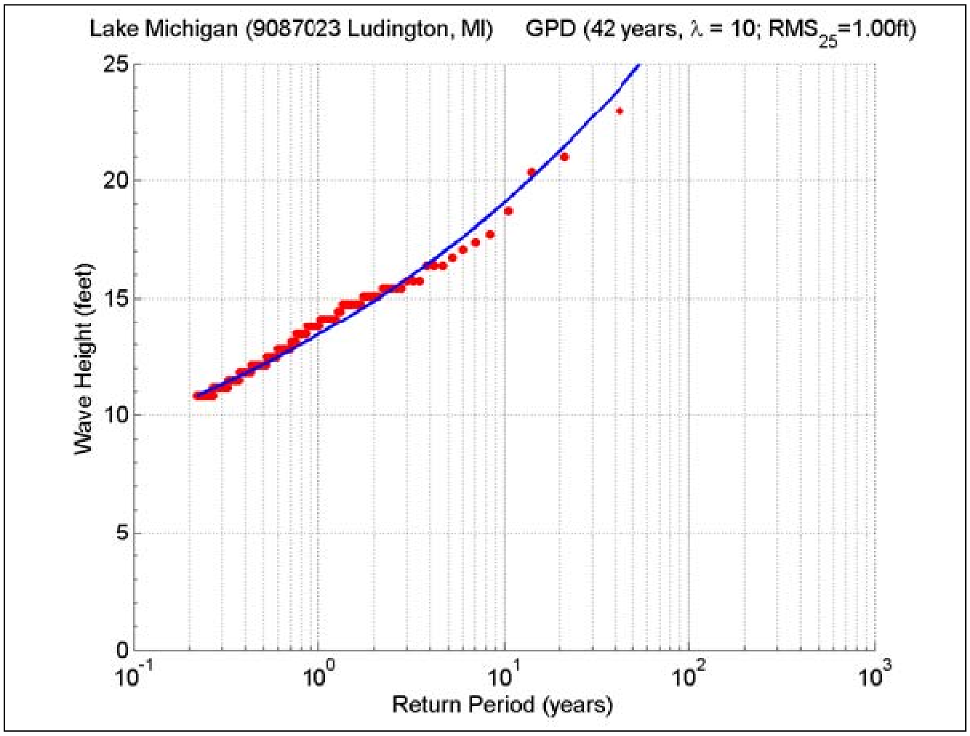

Figure 69. Ludington WIS wave height PDS empirical distribution and extremal best fit using GPD.

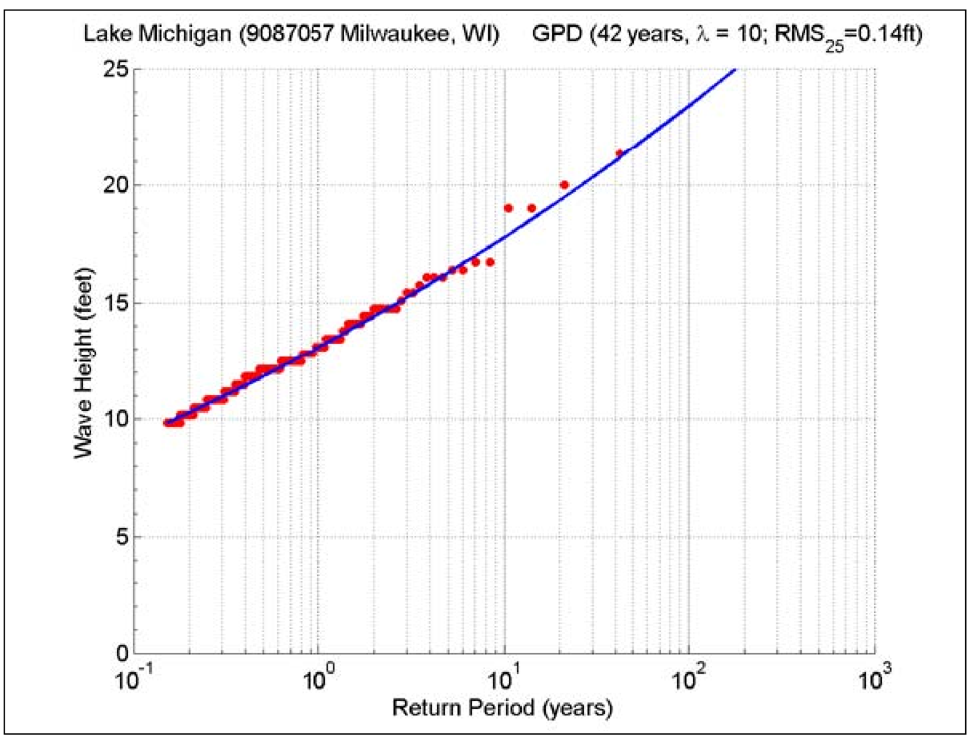

Figure 70. Milwaukee WIS wave height PDS empirical distribution and extremal best fit using GPD.

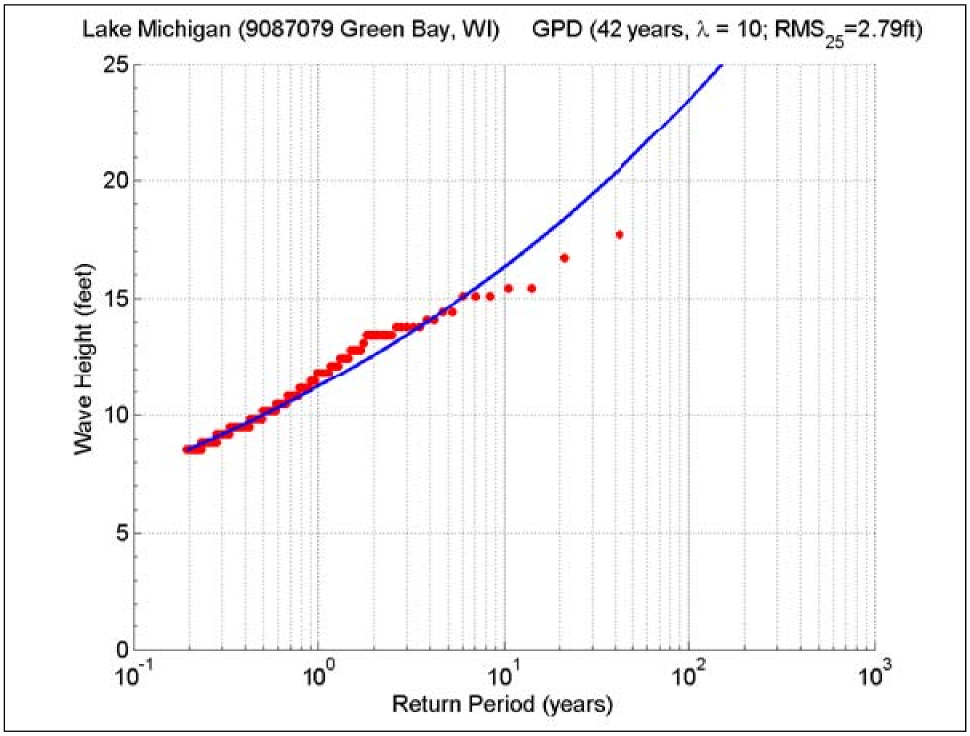

Figure 71. Green Bay WIS wave height PDS empirical distribution and extremal best fit using GPD.

The goal in this section is to accurately compute the extremal distribution of total water level. Total water level can include contributions from surge, wave runup (including wave setup), and other responses. In shallow water over irregular and time-varying bathymetry, storm surge and wave height combine to produce total water level in a complex and non-linear way. Surface ice and other factors previously discussed complicate this process. Previously published mapping guidelines relied on statistical prediction of the BFE using joint probability analysis and this is simply not very accurate if the physical processes are sufficiently complex to make the true joint probabilities unknown for reasons cited earlier. For total water level BFE's in the nearshore, this is often the case.

An improved method utilizes high-fidelity numerical hydrodynamic models to predict the total water level along the shore for a sufficient number of storms over 50 years to generate an accurate empirical distribution. Then this empirical distribution of total water level can be fit with a parametric distribution and the BFE estimated. Further, it is suggested that each storm be modeled on the actual lake level. In this way, water levels and waves can be verified using measurements where available and complex nearshore hydrodynamic processes contributing to total water level are correctly

modeled to achieve as accurate a solution as reasonably possible, using existing technology.

5.6 Wave runup

Wave runup prediction methods are investigated in detail in a companion report (Melby 2012) and will not be covered within this report. Herein we simply used the CSHORE numerical model to compute runup on representative beaches based on recommendations given by Melby (2012). Wave setup is included in the prediction given by CSHORE and is therefore intrinsic to all total water levels.

5.6.1 Beach profile example

The two percent exceedance value of wave runup ($R_{2\%}$) was computed for a beach profile near the Milwaukee water level gage. The profile location is shown in Figure 72, the profile transect in Figure 73 and the bathymetry in Figure 74. For this transect, the average beach face slope between the shoreline and 158 ft offshore is 1:33, the offshore slope between 158 ft and 1,813 ft offshore is 1:88, and the overall average slope between the shoreline and 1,813 ft offshore is 1:85.

5.6.2 CSHORE numerical model

CSHORE is a combined wave and current model based on time-averaged continuity, cross-shore and longshore momentum for the non-linear shallow-water wave equations (Kobayashi 2009). The model includes

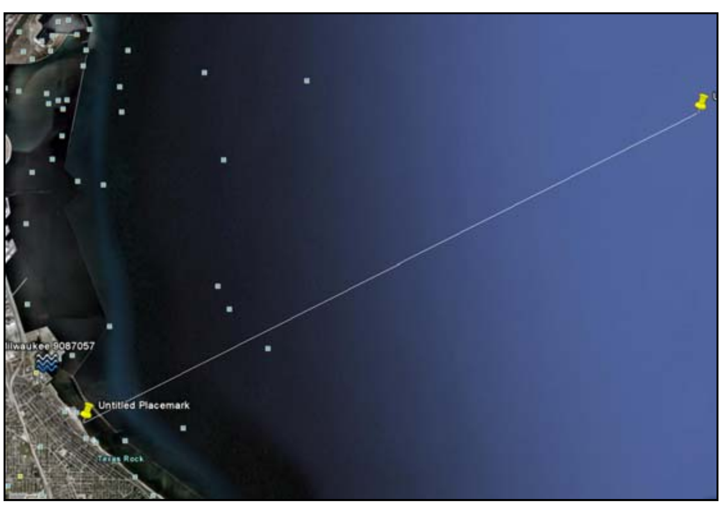

Figure 72. Beach transect and the location of Milwaukee water level station.

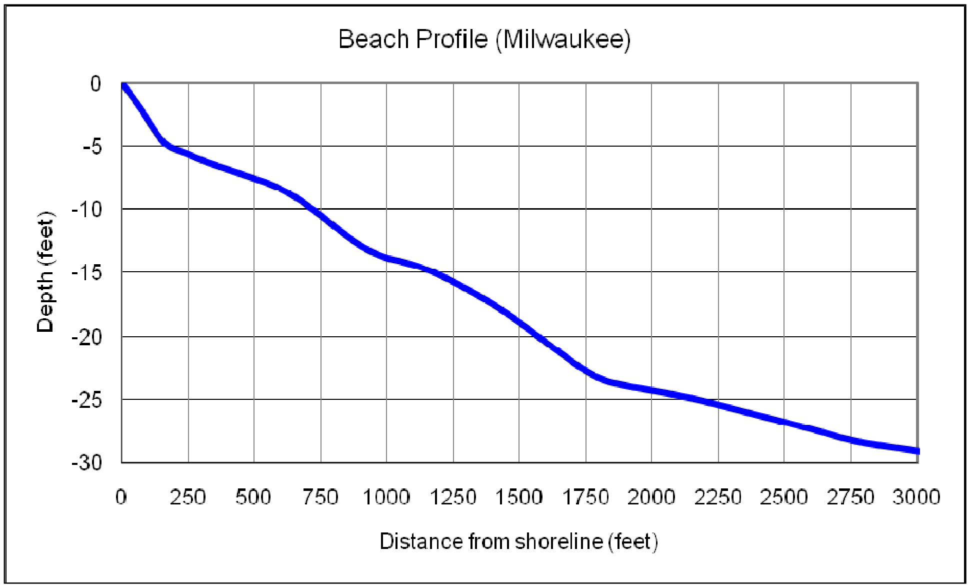

Figure 73. Beach profile for transect shown in Figure 71.

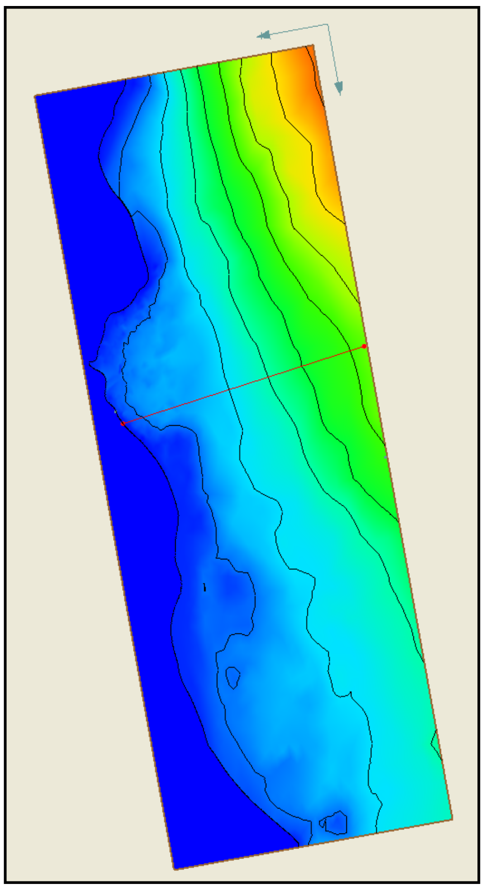

Figure 74. CMS-Wave grid extents, bathymetry and beach transect.

wave action and roller energy equations; a sediment transport model for suspended sand and bedload; a permeable layer model to account for porous flow and energy dissipation in rubble mounds, gravel structures and beaches; and a probabilistic model for an intermittently wet and dry zone on impermeable and permeable bottoms for the purpose of predicting swash, wave overwash and armor layer damage progression.

Waves were transformed from deepwater to a location just outside the surfzone using the numerical wave transformation program CMS-Wave. This location was roughly 1300 ft offshore in a water depth of 16.5 ft. CSHORE was then used to transform waves through the surfzone and compute wave runup on the beach face. For this analysis, CSHORE parameters were set according to recommendations given in Melby (2012). For all CSHORE analyses, the CSHORE settings were as follows IPERM=0, IOVER=1, IWTRAN=0, IPOND=0, IWIND=0, ITIDE=0, and ILAB=1, IWCINT=1, IROLL=1, GAMMA=0.5, RWH=0.01 m, DX = 1 m, and Friction Coeff = 0.001, where IPERM = 0 or 1 for an impermeable or permeable bottom, IOVER = 0 or 1 for no wave overtopping or wave overtopping at the landward end of the computation domain, IWTRAN=0 or 1 for no standing water or wave transmission in a bay or lagoon landward of an emerged dune or coastal structure, IPOND = 0 or 1 for no ponding or ponding on lee side of dune or structure, IWIND = 0 or 1 for no or yes for wind effects, ITIDE = 0 or 1 for no tide or inclusion of tide, ILAB = 0 or 1 for field data or lab data, IWCINT: 0 or 1 for no or yes for wave and current interactions, IROLL: 0 or 1 for no or yes for roller effects in the wet zone, GAMMA: empirical breaker ratio parameter, RWH: runup wire height, DX: constant grid mesh spacing, and Friction Coeff: bottom friction factor. CSHORE requires metric units.

5.6.3 Wave runup for top 10 storms

Wave runup and total water level for the transect near the Milwaukee water level gage are presented here as an example of the results. The wave runup results and total water level including runup are summarized in Table 24. Of the top 10 storms shown in this table, the first five (1 through 5) have the most extreme surge elevations for the gage location, while storms 6 through 10 have the most extreme wave heights.

Table 24. Wave runup results for top 10 storms for beach profile near Milwaukee gage.

Year	Month	Surge (ft)	Offshore H_{m0} (ft)	Nearshore H_{m0} (ft)	CSHORE $R_{2\%}$ (ft)	Total Water Level (ft, IGLD85)
1987	3	2.13	14.11	9.25	5.81	588.2
1987	12	1.95	16.40	9.62	6.09	587.6
1990	12	1.78	14.11	9.24	6.04	586.5
1985	3	1.61	10.83	7.27	4.11	586.9
1971	12	1.52	9.19	6.95	3.58	585.5
1974	2	1.24	19.03	9.48	6.80	585.5
1984	2	1.03	19.03	9.62	6.31	585.1
1973	12	0.96	16.73	9.11	5.79	585.3
1987	12	1.95	16.40	9.62	6.09	587.6
1993	4	1.36	16.40	9.62	6.33	586.6

6 Total Water Level Distributions

The preceding discussion suggested that accuracy of BFE predictions would be maximized if the water levels were accurately modeled for all significant storms at each transect and these results used to produce water level extremal distributions. This is achieved through high-fidelity modeling of each storm from deep water to shallow water and up the beach, structure or overland and then computing the total water level distribution from these results. Clearly, if *all* significant storms were completely modeled, it would be a simple task to assemble the results and compute the BFE at each transect. Although it is possible to model all storms using sophisticated numerical hydrodynamic models, it is not reasonable at this time due to technological constraints, computational requirements and time and funding constraints. An additional constraint is the limited quality meteorological data (e.g. wind and atmospheric pressure) and ice coverage data prior to 1970.

One of the technological constraints in map production is modeling overland flow. WHAFIS is typically used to model overland flow on transects. However, this model is used to model a single 100 yr flood, rather than each storm. A model with similar capability that can model flooding for individual storms over land, through buildings, various types of vegetated land, and other complex land types will not be available for production mapping in the immediate future. So for transects involving overland flow, it is expected that map production will be similar to what has been used in the past and was discussed in Chapter 1 under the heading *Existing FEMA mapping guidelines*. The following discussion for a preliminary flood mapping strategy is exclusive of overland flow.

The challenge of a map production methodology is to use high-fidelity numerical hydrodynamic models to model as few storms as possible over the shortest record length possible such that an accurate approximation of the total water level extremal distribution is computed with an estimable uncertainty. An essential requirement is that the tail of the water level distribution be accurate so that extrapolation to BFE value is accurate. We previously determined that a 50-yr record length is the minimum requirement. Some simple analyses were conducted to determine that roughly 150 storms would be required to accurately model the extremal

distributions. In the following this number will be investigated in more detail.

For Lake Michigan, based on the preceding discussion, a trial simulation using 50 years of wave and water level data with 20 modeled storms over this duration for each water level gage location is considered the minimum acceptable population to achieve a reasonable approximation of the total water level distributions. The 20 storms per station to be modeled are selected from the rank ordered lists of measured surge and WIS wave heights as the top 10 storms by wave height and the top 10 storms by surge. Because all storms are modeled over the entire lake, the total number of events at each transect is roughly 180.

6.1 Composite total water level population

The preliminary methodology to develop total water level distributions used in the following trial is as follows:

1. Select a set of the most extreme 20 storms at each of the nine water level gage locations to yield 180 unique extreme events.
    a. For this trial, the events to be modeled are primarily selected based on gage measurements of surge and WIS wave heights. WIS stations are selected nearest each water level gage. Not all wave gage locations have nearby WIS stations (e.g. Green Bay, Sturgeon Bay, and Mackinaw City). Herein, the closest WIS station is used.
    b. Each set of top 20 storms for each water level station is constructed by selecting the 10 storms with the highest measured surges and the 10 storms with the highest WIS wave heights. This yields a total of 180 storms when all of the stations are combined.
    c. The objective is to identify a set of at least 180 unique storms. However, of the initial set of storms, approximately half are duplicated storms. Each of the duplicated storms is deleted from the set and replaced with the next storm from the appropriate rank-ordered list from the same gage. For example, if a surge event is a duplicate, it is deleted and replaced with the next highest event in the rank-ordered list of surges. After replacing all duplicate events, the total number of storms per station is 20 and all 180 events are unique.
2. For the final map production, the selected events are modeled to determine the wind and pressure over the lake, surge, and offshore waves. It is expected that wind and pressure fields would be CFSR or from the Natural Neighbor method, as described in the companion report (Jensen et al. 201),

and the output would be used to drive the ADCIRC surge model and the WAM offshore wave generation model. The waves would be transformed to nearshore using appropriate wave transformation model and then transformed past the shoreline where runup is determined as described in the preceding chapter. The storms are expected to be modeled on the actual lake level to calculate the most accurate prediction of total water level possible. For this trial, the WIS waves were transformed to nearshore using CMS-Wave and then up the beach using CSHORE on the actual lake levels to determine total water level for select transects near water level gage sites.

3. The 180 total water levels are rank ordered, plotting position computed, and the distribution fit with a suitable extremal distribution for each transect. Then the BFE is selected from this best-fit distribution.

This preliminary methodology is general and does not specify many of the details that are covered in the Mapping Guidelines documents. This methodology will be developed further and reported in the companion report Nadal-Caraballo et al. (2012) and these recommendations will be reflected in the revised mapping guidelines reports (FEMA 2012).

6.2 Actual total water level population

To determine the accuracy of the trial methodology, the actual total water level distributions were determined at each gage. The actual total water level distributions were determined by selecting the most extreme 100 surge and 100 wave height events from the water level gage measurements and WIS wave heights, respectively, for a total of 200 events per station. Water level gage station locations where values were calculated were Calumet, Milwaukee, Kewaunee, Port Inland, Ludington, and Holland. The WIS waves from the WIS station closest to the wave gage location were transformed to nearshore and CSHORE used to calculate runup on the actual measured water level for that event. A typical beach cross-section on the open coast near each gage location was used, similar to that described above for Milwaukee. The resulting total water level population was rank ordered and plotting position calculated. The highest 56 events by total water level were selected as the PDS and fit with a GPD. This is equivalent to using the POT method with a sample intensity of two events per year. This population is termed *actual* in the following.

Note that a nearly equivalent analysis was completed for the AMS rather than the PDS and the two methods are compared in the following section.

6.3 Comparison of preliminary methodology with actual total water level distributions

In this section, the actual total water level probability distributions derived from measured data are compared to the composite distributions developed based on the above stated methodology. For this analysis, there were no recently modeled storms. This restricted the time period of analysis to the 28 years from 1970 to 1997, during which concurrent water level and WIS wave data were available. This is a significantly shorter record length than the recommended period for the methodology of 50 years (1960 – 2010).

The above described trial composite methodology was used to predict the total water level distributions for comparison with the actual water level distributions. The most extreme 10 surge and 10 wave height events for a total of 20 events per station were selected from the water level gage measurements and WIS wave heights for each of the nine water level gage locations to achieve 180 unique events. Each wave condition was transformed to nearshore using CMS-Wave and then up the beach using CSHORE at all stations. The resulting 180 total water levels were rank ordered and the top 56 values selected as the PDS. The resulting empirical distribution was fit with the GPD for each gage location. This population is termed “composite” in the following.

The results of these computations, as well as the RMS deviations, are compared in Table 25. RMSD is the RMS deviation of the empirical TWL distribution from the best fit parametric GPD. Figures 75 - 78 illustrate both sets of data for example sites of Ludington and Milwaukee. In all plots, the “actual” empirical distributions are identified by red diamonds and best-fits are shown as blue curves. As shown in Table 25, differences in total water level are minimal.

An exception occurred for the Kewaunee gage. The difference between actual and composite for Kewaunee is primarily a result of a single storm (outlier). This storm, although of moderate surge and wave height, occurred on a top five water level, thus resulting in high runup and top overall total water level. During production modeling within the mapping process, it may be necessary to add this storm, as well as any other storms that are below surge and wave height threshold, but are known to have occurred and caused significant flooding.

Also, from Table 25, note that the total water level predicted at Calumet is at least six feet higher than that estimated at other stations. These differences are a result of higher runup on the steep beach slope (1:10) of the Calumet transect.

Table 25. Actual total water level (TWL) BFE's compared to recommended methodology (composite).

	RMSD (ft)			100-yr TWL (ft)			500-yr TWL (ft)		
	Actual	Composite	Difference	Actual	Composite	Difference	Actual	Composite	Difference
Ludington	0.12	0.15	0.03	585.29	585.29	-0.04	585.29	585.34	0.05
Holland	0.37	0.29	-0.08	588.80	588.73	-0.06	589.11	589.04	-0.07
Calumet	0.14	0.26	0.12	595.29	595.29	0.00	595.40	595.46	0.06
Milwaukee	0.27	0.21	-0.06	587.50	587.48	-0.02	587.71	587.76	0.04
Kewaunee	0.29	0.16	-0.13	587.08	586.21	-0.87	587.28	586.28	-1.00
Port Inland	0.29	0.39	0.10	589.25	589.20	-0.06	589.44	589.62	0.18

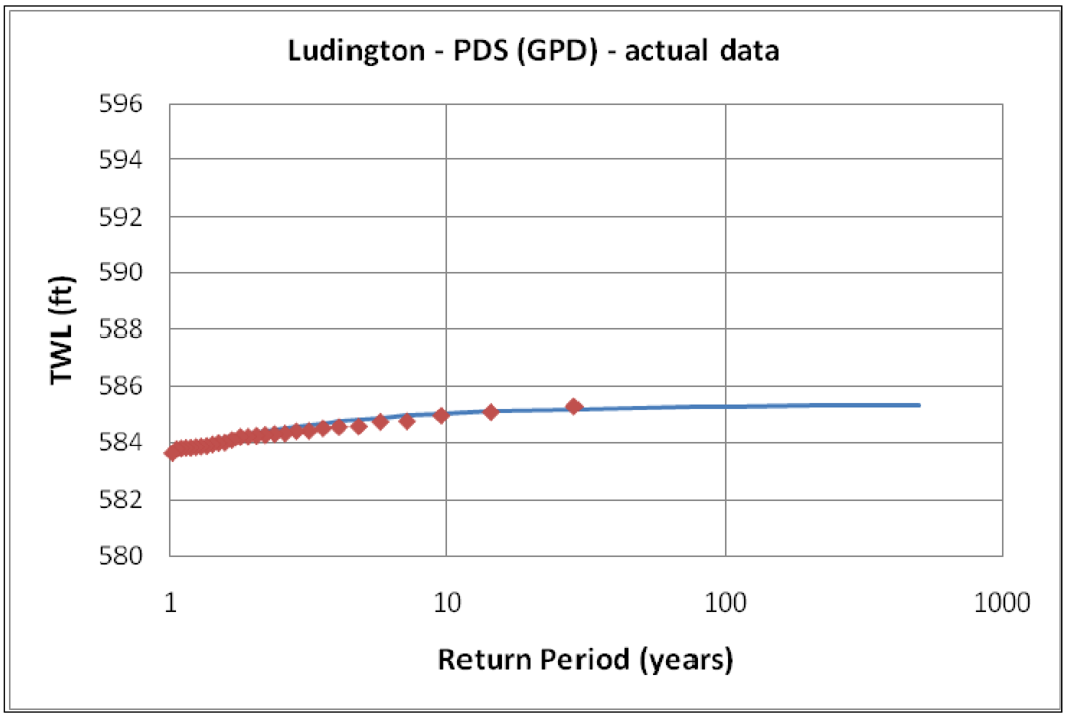

Figure 75. Empirical distribution from PDS of actual total water level (points) and best fit GPD of actual total water level (line) for Ludington.

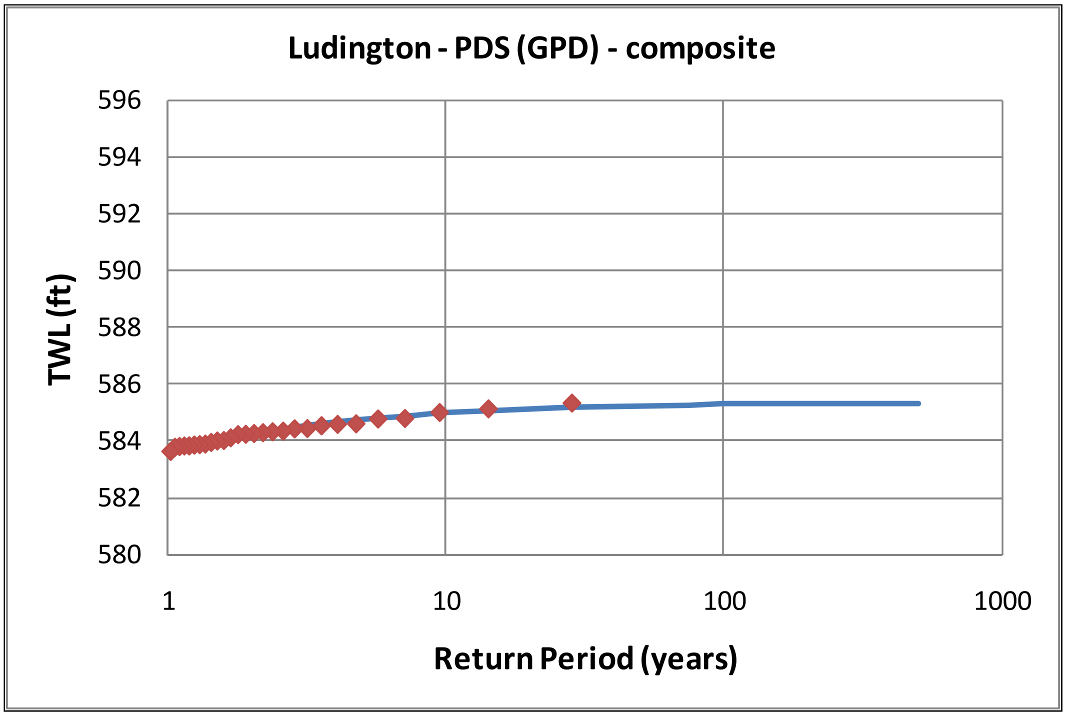

Figure 76. Empirical distribution from PDS of actual total water level (points) and best fit GPD of composite (line) for Ludington.

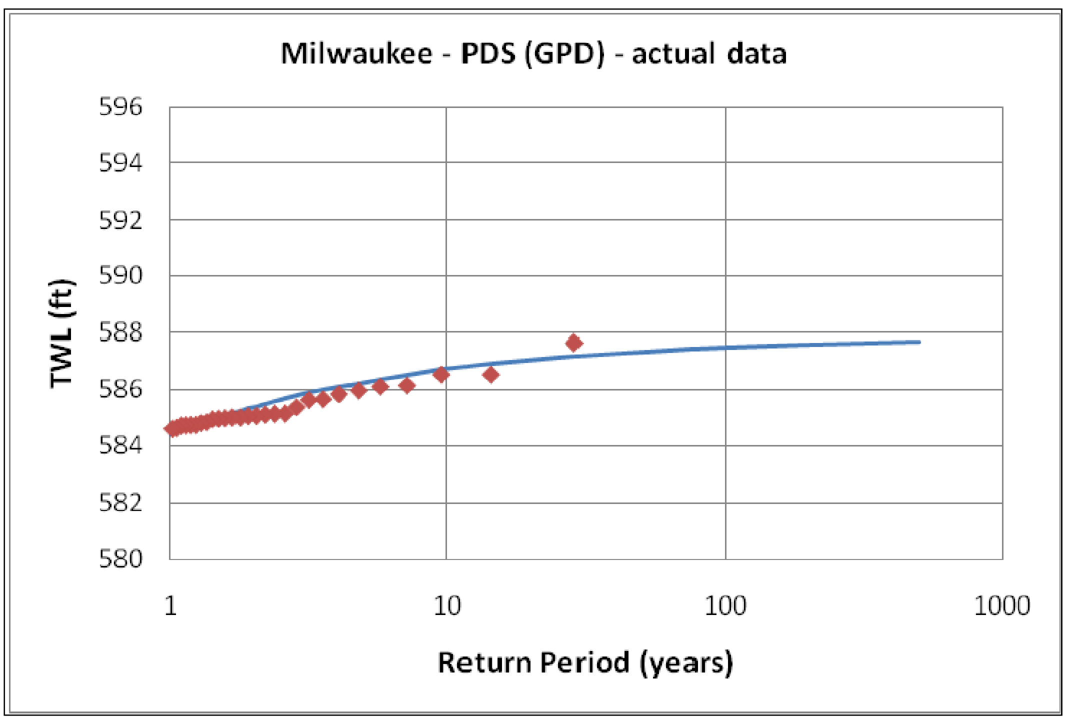

Figure 77. Empirical distribution from PDS of actual total water level (points) and best fit GPD of actual total water level (line) for Milwaukee.

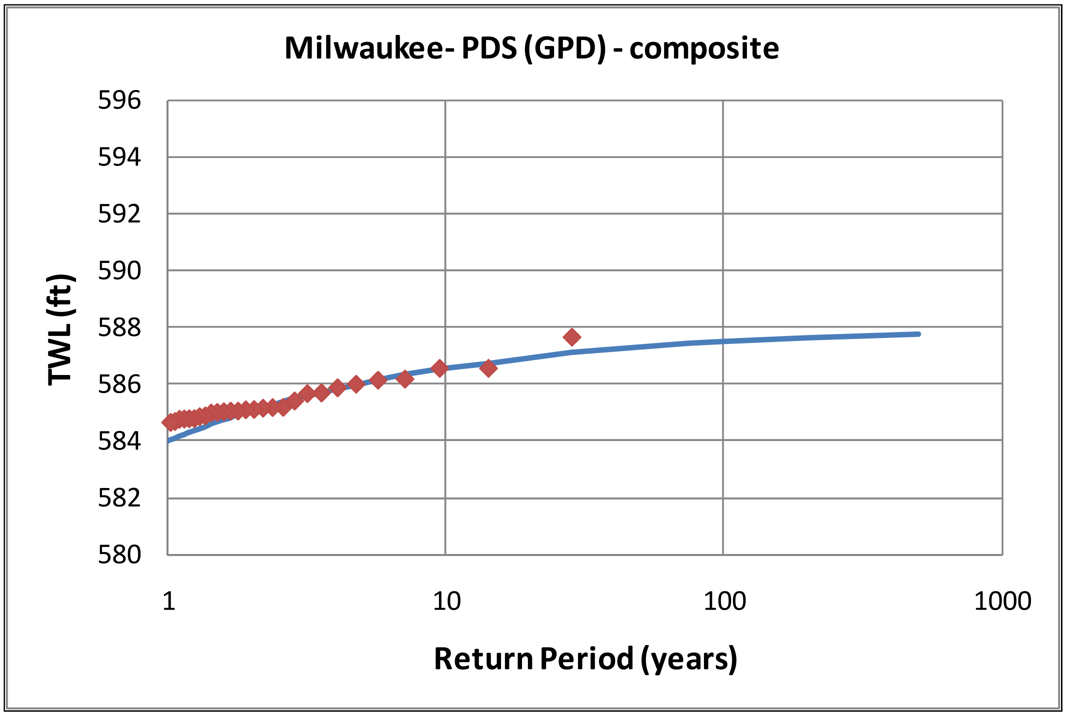

Figure 78. Empirical distribution from PDS of actual total water level (points) and best fit GPD of composite (line) for Milwaukee.

6.4 Annual maximum compared to partial duration series

Statistics derived from the analysis of total water level annual maximum series (AMS) and partial duration series (PDS) are shown in Table 26, both computed using the recommended trial methodology. Plots of the total water level AMS and PDS best fit curves are shown in Figures 79 – 80 for example sites. For AMS, the Generalized Extreme Values (GEV) distribution was used to fit the extremal total water level empirical distribution data while the PDS GPD are the same as shown in the figures above. Note that the AMS values can be on high and low lake levels because there is one extreme from each year. This compares with the PDS values which tend to be on high lake levels. However, PDS values may be on lower lake levels, depending on the magnitude of the surge and runup. As noted previously in this report, the AMS distribution is steeper than the PDS distribution. This is a result of having fewer extreme events in the AMS and is similar to having too short a series duration (not enough years). The results of the AMS-PDS comparison suggest that the PDS methodology is more accurate in modeling extreme water levels and therefore predicting the BFEs.

Table 26. Recommended methodology results: annual maximum series compared to partial duration series.

	RMSD (ft)			100-yr TWL (ft)			500-yr TWL (ft)		
	AMS	PDS	diff	AMS	PDS	diff	AMS	PDS	diff
Ludington	0.14	0.15	0.01	585.50	585.29	-0.21	585.87	585.34	-0.53
Holland	0.22	0.29	0.06	589.07	588.73	-0.34	590.04	589.04	-1.00
Calumet	0.41	0.26	-0.15	595.31	595.29	-0.03	595.53	595.46	-0.07
Milwaukee	0.21	0.21	0.00	589.22	587.48	-1.73	591.90	587.76	-4.14
Kewaunee	0.18	0.16	-0.01	586.47	586.21	-0.25	586.90	586.28	-0.62
Port Inland	0.30	0.39	0.09	589.60	589.20	-0.41	590.59	589.62	-0.97

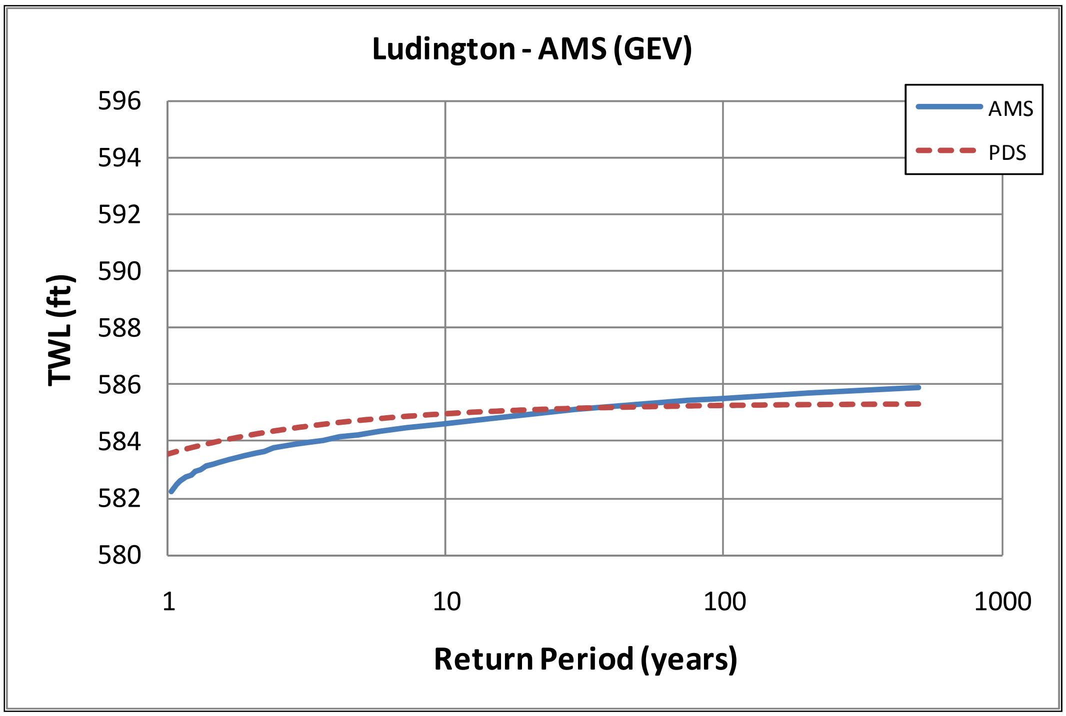

Figure 79. AMS and PDS total water level best-fit parametric distributions from recommended methodology for Ludington.

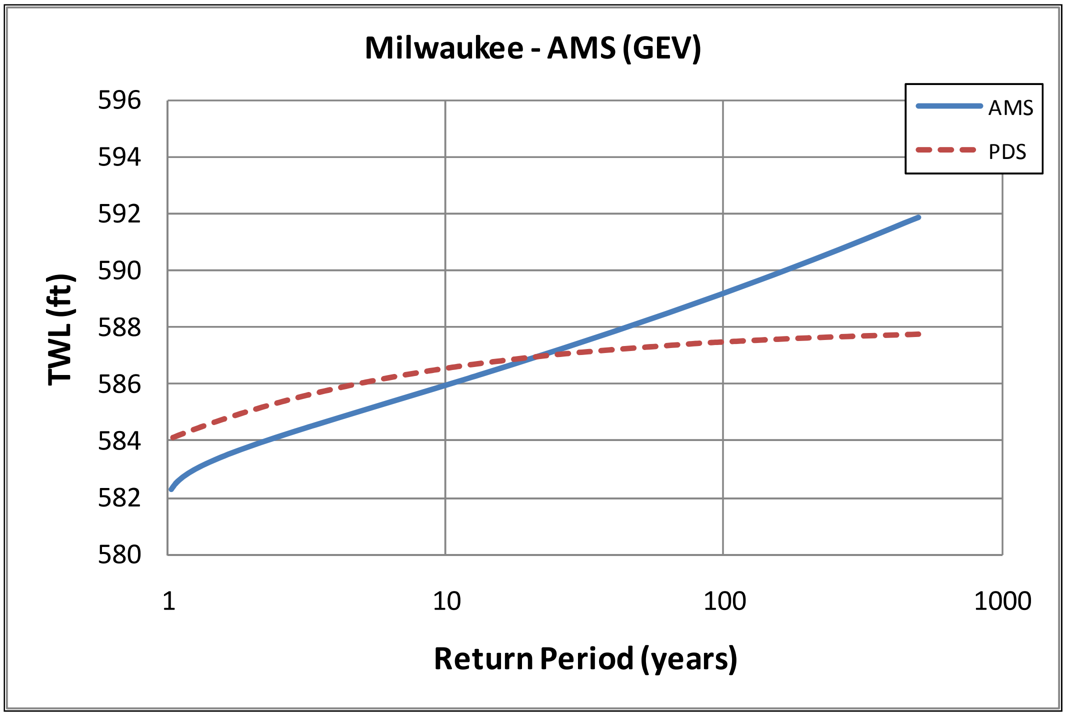

Figure 80. AMS and PDS total water level best-fit parametric distributions from recommended methodology Milwaukee.

7 Uncertainty in TWL Probability Distributions

The total water level is a combination of several components, including: long-term water level, tide, surge, seiche, and runup. Each component has a certain amount of uncertainty in both the measured and modeled values. Natural random variation in measurements is termed aleatory uncertainty. Additional uncertainty from our limited knowledge of these complex processes or simplifications or limitations of numerical models is termed epistemic uncertainty. There are some processes that might not be included in our predictions that may be important for a small number of events or our analytical or statistical treatment may be too simple. The total uncertainty from all of these contributions is significant so predicting the total uncertainty should be an essential part of the water level analysis. Unfortunately, we can only estimate some uncertainties because in some cases, *we don't know what we don't know*. However, our goal should be to construct a methodology where the significant uncertainties can be quantified. The recommended methodology has been developed to maximize our ability to quantify the total uncertainty. In this section, we provide a very brief and crude estimation of uncertainties to illustrate how this information can be useful in flood mapping.

7.1 A non-exhaustive list of sources of uncertainty in total water level estimation

1. Water level, wave, wind, ice measurement random error and bias;
2. Sparse measurements of winds, water levels, and waves;
3. Numerical model error and bias;
4. Natural variability not accounted for in the methodologies;
5. Models missing peak because of wind resolution;
6. Lumping multiple processes into a single statistical family;
7. Stationarity assumption – is the probability distribution changing with time?
8. Translation of plotting position from gage sites to other spatial locations;
9. Influence of extreme outliers – unknown probability;
10. Unknown physics of ice on wind-wave and surge generation;
11. Anthropogenic impacts on lake levels;
12. Future climate change.

Here we will assume that the uncertainties are independent (probably not reasonable) and can be superimposed using the *quadrature* method, in which standard errors, or deviations, are summed as follows:

$$U_{total} = \sqrt{(U_1)^2 + (U_2)^2 + \ldots + (U_n)^2}$$

This method assumes that the uncertainties associated with each component are independent from each other and normally distributed, which also requires further analysis.

The uncertainties included in this uncertainty budget example are:

1. NOAA water level measurements and datum errors;
2. Errors associated with the use of 1-hr recorded data as opposed to the more accurate 6-min data;
3. Uncertainty associated with CSHORE runup estimates;
4. Uncertainty associated with the probability distribution fit.

7.2 NOAA water level measurements and datum errors

Gibson and Gill (1999) discuss that typical measurements errors are 0.33 ft at 95 percent confidence level; likewise, datum errors are typically 0.66 ft. The total of 1-ft at 95 percent confidence level is equivalent to a standard error of 0.50 ft.

7.3 Data scattering: 6-min vs. 1-hr

Analysis of the data scattering yielded the standard errors listed in Table 27.

Table 27. Standard error associated with data scattering.

Station	Station Number	Standard Error (ft)
Ludington, MI	9087023	0.12
Holland, MI	9087031	0.04
Calumet Harbor, IL	9087044	0.25
Milwaukee, WI	9087057	0.13
Kewaunee, WI	9087068	0.18
Port Inland, MI	9087096	0.10

7.4 Runup computation uncertainty

CSHORE standard error = 0.10 ft

7.5 Probability distribution uncertainty

The Bootstrapping by Monte Carlo method was used to estimate the uncertainty associated with the probability distribution fit using the generalized Pareto distribution (GPD). The basis of this method is that the fit is assumed to be correct. Total water level values were randomly sampled from the probability distribution to construct a population similar to the original data set. In this case 10,000 re-samples were generated. The standard errors were computed at several different return periods from this population.

7.6 Total uncertainty and confidence intervals

The total water level distributions and their respective 95 percent confidence intervals are plotted in Figures 81 - 82 for the representative gages. A 95 percent percent confidence level is bound by 2.5 percent and 97.5 percent confidence limits. A confidence level of 95 percent is equivalent to 1.645 times the standard error. One can say that there is a 95 percent chance that the expected, or 'true', 100-year flood level is bound by the upper and lower confidence limits. In other words, the true total water level value will not exceed the upper confidence limit 97.5 percent of the time, or will exceed the upper confidence limit just 2.5 percent of the time.

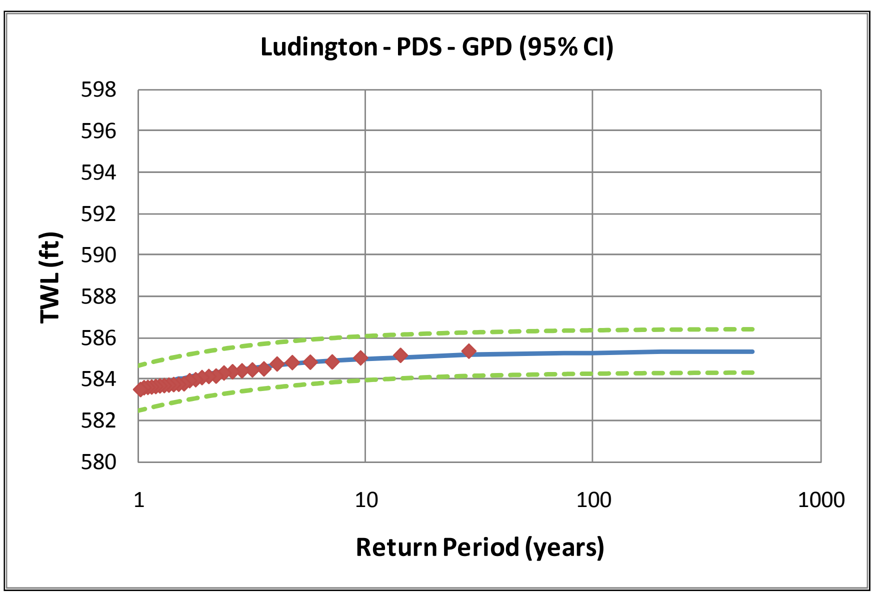

Figure 81. Total water level confidence intervals for Ludington.

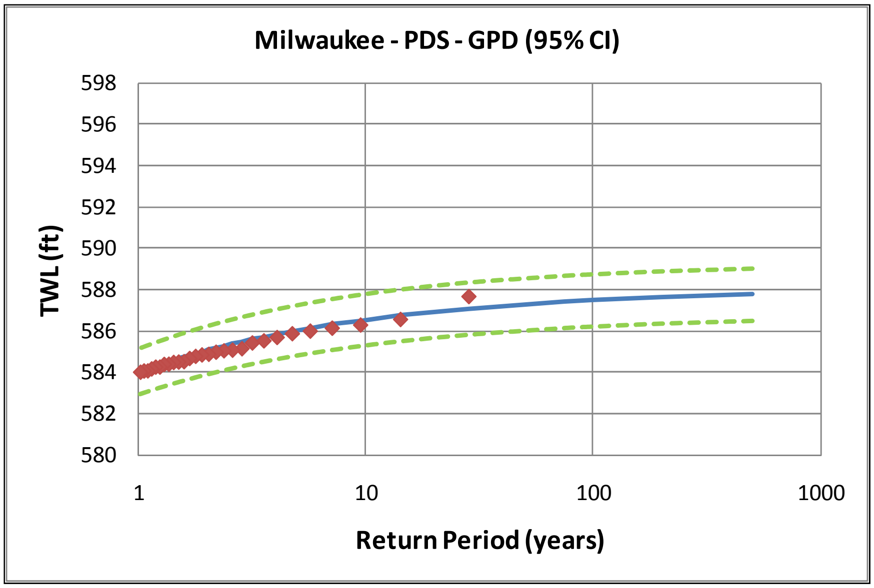

Figure 82. Total water level confidence intervals for Milwaukee.

8 Conclusions

The Great Lakes are subject to coastal flooding as a result of severe storms. Strong winds blowing across the surface of the lakes produce high waves and surge. Variations in lake levels due to decadal scale variations in precipitation and anthropogenic activities affect the risk of flooding. In this report, historical storm climatology on Lake Michigan and the resulting measured waves and water levels are analyzed in detail. The characteristics of the driving forces that produce coastal flooding are investigated. The detailed history of water level and wave time series and associated probabilities are calculated. Long term, seasonal, and event time scales are separately analyzed. Various parametric correlations between time scales and between spatial locations are quantified.

The results show that long term water levels are stationary. Extreme values of water levels are mostly due to strong non-convective storms that occur from November to April. These storms move east across the continent from the Rocky Mountains and mostly move SW to NE. Most strong storms are low pressure systems with leading winds blowing from the S to SW and trailing winds blowing from the N to NE. Strong winds from these events tend to align with Lake Michigan and Green Bay long fetch lengths. These storm systems can be complex with one or two pressure systems over Lake Michigan simultaneously. Wind, pressure, ice and lake seiching can combine to make analysis challenging. Convective thunderstorms also produce high waves and surge on the lake, mostly during the summer months. However, it was found that the influence of these events on the extremal distribution is not significant enough to treat them as a separate population.

Correlation between surges at different water level gages was shown to be low. There was no correlation between long term and event scale water levels or event scale wave heights.

It was shown that extremal water level distributions require roughly 50 years of data to obtain the correct shape. Shorter time periods produced exceedance probability distributions that were too steep and often greatly over-predicted BFEs. Similarly, annual maximum series (AMS) of surge and wave heights were compared to partial duration series (PDS) and the AMS

generally were too steep. This was the result of too few extreme events in the series because significant events were discarded if more than one significant event occurred in any given year.

A new flood map production trial methodology is proposed to improve the accuracy of the BFE estimates as well as allow quantification of uncertainties. The methodology is founded on a suite of accurate estimates of total water level from all significant events over a sufficiently long record length. These estimates are determined using high-fidelity planetary boundary layer and hydrodynamic models for regional wind and pressure, waves, storm surge, wave transformation, and wave setup and runup up the beach or onto structures. The trial screening methodology is proposed and tested that minimizes the number of events for high-fidelity modeling and maximizes accuracy of total water level distribution.

The trial methodology was illustrated with a simple screening process that utilized a subset of extreme measured surge values and WIS wave heights to develop a suite of storms to model. The 10 most extreme surge events and 10 most extreme wave height events at each wave gage location were selected. Given nine water level gage locations on Lake Michigan, 180 events were selected using rank-ordered measured surge and WIS hindcast waves. It was noted that the screening process may require adding a few storms that did not make the list but were known to cause significant flooding for any given transect. A PDS was selected from this population of total water levels and the generalized Pareto distribution was used as best-fit. The 1-percent and 0.2 percent AEPs were determined from this distribution.

For six stations around Lake Michigan, the new method was compared to the actual total water level distributions computed from a PDS constructed of the top 200 storms from each station. This method showed fairly small errors. The population of resulting modeled water levels at each transect was shown to provide a reasonable estimate of actual water levels determined from a population of extremes that was 10 times larger.

Quantifiable uncertainty is an important criterion when evaluating any methodology. It was shown that the uncertainty is generally quantifiable and an example is shown.

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Appendix A: Basic Probability Concepts

Probability of an event

Probability of an event can be computed from data using the following procedure.

A set of successive measurements must be reduced to a partial duration series or annual maximum series to determine the extremal probability. The annual maximum is simply the maximum measurement for a given calendar year. The partial duration series is computed using the peaks-over-threshold technique.

Peaks-Over-Threshold technique

The POT extreme identification sampling technique is widely used for extraction of extreme values from time series of wave climate data. The main concern is that the POT method suffers from lack of general guidance for its application (Lang et al. 1999). The sampled peak exceedances must be independent and identically distributed (i.i.d.), and their occurrences should be described by a Poisson process (Luceño et al. 2006). When applying the POT technique, the most significant parameters are: (1) time lag required for extreme events to be considered i.i.d., or inter-event time, τ; (2) number of individual storms per year or sample intensity, λ; and (3) H_{th}, threshold wave height. The semi-automated method of Thompson et al. (2009) is used herein with a modification to limit the initial search to wave heights that exceed the mean wave height.

Probability distribution

Once the series of maxima are computed, the series is rank ordered from highest to lowest value to determine the empirical probability distribution. The plotting position can be computed using a variety of formulas. The formulas have the form $(r - a)/(n + 1 - 2a)$ where r is the ordered rank of the sample, n is the number of data points in the sample and a is in the range from 0 to 1/2. The most common plotting position formula is the Weibull formula $P = \underline{r}/(n+1)$ which gives the empirical exceedance probability for points ranked from highest to lowest.

If the exceedance probability is defined as the annual exceedance probability of an event, then the return period is defined as the inverse of the probability that an event will be exceeded in a given year. The equation for computing the average recurrence interval or return period is

$$T = -\frac{1}{\ln(1-P)} \qquad P = 1 - \exp\left(-\frac{1}{T}\right)$$

For large T, $T = 1/P$ can be used. The error is 0.5 percent for $T = 100$, 1 percent for $T = 50$, and 5.4 percent for $T = 10$.

Annual exceedance probability: *P*

The probability that an event level will be met or exceeded during a one-year interval.

Binomial distribution

The probability of $X = x$ occurrences in n independent trials if p is the probability of an occurrence in a single trial is given by

$$\Pr(X = x) = \binom{n}{x} p^x (1-p)^{n-x} \qquad x = 0, 1, 2, \ldots, n$$

where the binomial coefficient is

$$\binom{n}{x} = \frac{n!}{x!(n-x)!}$$

For example, to compute how many times a 20-yr flood will occur in a 40-yr period, $R = 20$, $p = 1/R = .05$, and $E(X) = np = 40(0.05) = 2$. The probability of exactly two floods with return period of 20 yrs occurring in a 40-yr period can be computed as

$$\Pr(X = 2) = \binom{40}{2} 0.05^2 (1-0.05)^{40-2} = \frac{40!}{2!(40-2)!} 0.0025(0.95)^{38} = 0.28$$

Similarly, the probability of a 10-yr flood in 10 yrs is $Pr(X = 1) = 0.39$.

As another example, we want to compute the probability of one or more 100-year floods in a 30-year mortgage period. Here we are interested in the exceedance probability $Pr\ (X \geq 1) = 1 - Pr(X = 0)$. The number of occurrences is $x = 0$, the number of trials is $n = 30$, and the annual probability of the occurrence is $p \sim 1/100 = 0.01$. So the probability of getting one or more 100-year floods in 30 years is

$$\Pr(X = 0) = 1 - \binom{30}{0} 0.01^{0} (1 - 0.01)^{30-0} = 1 - \frac{30!}{0!*30!}(1)(0.7397) = 1 - 0.74 = 0.26$$

For computing the probability of a flood of return period R with annual probability of $p \sim 1/R$ occurring in an n-year period, the binomial distribution equation reduces to

$$\Pr(X = 0) = 1 - (1 - p)^{n}$$

The 500-yr return period has an annual probability of two percent. Over a typical mortgage term of 30 years, there is a six percent chance of seeing at least one 500-yr return period flood.

Distributions of maxima

According to extreme value theory, annual maxima should fit to the generalized extreme value distribution.

$$F(x) = \exp\left[-\left(1 + \frac{c(x-a)}{b}\right)^{-1/c}\right]$$

where a = threshold value of x; b, which is greater than zero, is the scale; and c is the shape. This distribution reduces to the Weibull for $c<0$, the Fisher-Tippet II for $c>0$ and the Gumbel or Fisher-Tippett I for $c=0$. Extreme value theory suggests that the distribution of POT maxima should conform to the generalized Pareto distribution (GPD)

$$F(x) = 1 - \left(1 + \frac{c(x-a)}{b}\right)^{-1/c}$$

The GPD reduces to the exponential distribution as c approaches zero.

Appendix B: Storm Summaries

This appendix summarizes some significant storms on Lake Michigan.

Table B1. Top 5 surge-ranked storms with peak surge and coincident meteorological data.

Water Level Gage Station: Ludington, MI, 9087023								
Rank	Year	Month	Day	Surge (ft)	Wind Speed (ft/s)	Wind Direction (deg, Az)	Sea Level Pressure (millibar)	Air Temperature (°F)
1	1964	2	N/A	1.51	42	210	1008.4	48.92
2	1969	1	N/A	1.49	37	260	1013.7	3.02
3	1985	3	4	1.32	51	230	995.6	37.04
4	1966	4	N/A	1.30	N/A	N/A	N/A	N/A
5	1982	1	23	1.29	52	250	997.4	6.08
Water Level Gage Station: Calumet, IL, 9087044								
Rank	Year	Month	Day	Surge (ft)	Wind Speed (ft/s)	Wind Direction (deg, Az)	Sea Level Pressure (millibar)	Air Temperature (°F)
1	1929	10	21	3.50	41	310	1006.2	26.96
2	1965	12	24	3.31	41	230	997.3	17.06
3	1960	3	N/A	3.25	51	250	993.3	35.96
4	1989	9	22	3.06	59	250	982.5	32
5	1998	5	31	2.82	34	270	995.3	24.98
Water Level Gage Station: Kewaunee, WI, 9087068								
Rank	Year	Month	Day	Surge (ft)	Wind Speed (ft/s)	Wind Direction (deg, Az)	Sea Level Pressure (millibar)	Air Temperature (°F)
1	1990	9	4	2.45	29	220	1018.8	75.92
2	1995	6	1	1.99	17	220	1013.8	80.96
3	2002	8	4	1.95	13	260	1018.2	68
4	1992	11	2	1.52	31	90	1004	39.92
5	1973	10	15	1.40	27	310	1015.2	64.94
Water Level Gage Station: Green Bay, WI, 9087078, 79								
Rank	Year	Month	Day	Surge (ft)	Wind Speed (ft/s)	Wind Direction (deg, Az)	Sea Level Pressure (millibar)	Air Temperature (°F)
1	1990	12	3	5.41	44	50	1008.1	23
2	1965	12	24	3.76	34	20	1017.9	26.06
3	1993	4	15	3.49	46	30	999.2	33.98
4	1973	4	9	3.34	51	40	1009	30.02
5	1961	4	N/A	3.14	47	45	987.1	37.94

Water Level Gage Station: Holland, MI, 9087031								
Rank	Year	Month	Day	Surge (ft)	Wind Speed (ft/s)	Wind Direction (deg, Az)	Sea Level Pressure (millibar)	Air Temperature (°F)
1	1990	12	4	2.01	41	310	1006.2	26.96
2	1985	12	2	1.75	41	230	997.3	17.06
3	1971	12	30	1.58	51	250	993.3	35.96
4	1982	4	3	1.55	59	250	982.5	32
5	1982	1	4	1.47	34	270	995.3	24.98
Water Level Gage Station: Milwaukee, WI, 9087057								
Rank	Year	Month	Day	Surge (ft)	Wind Speed (ft/s)	Wind Direction (deg, Az)	Sea Level Pressure (millibar)	Air Temperature (°F)
1	1987	3	9	2.13	49	20	1022.2	24.98
2	1987	12	15	1.95	59	40	987.5	32
3	1990	12	3	1.78	54	60	1006.2	32
4	1985	3	4	1.61	49	90	1013	28.04
5	1998	3	9	1.53	54	360	1003.2	30.2
Water Level Gage Station: Sturgeon Bay, WI, 9087072								
Rank	Year	Month	Day	Surge (ft)	Wind Speed (ft/s)	Wind Direction (deg, Az)	Sea Level Pressure (millibar)	Air Temperature (°F)
1	1953	5	N/A	2.25	N/A	N/A	N/A	N/A
2	1954	3	N/A	2.14	N/A	N/A	N/A	N/A
3	1996	6	29	2.00	27	240	1007.9	95
4	1997	9	23	2.00	22	30	1025.5	60.98
5	1993	7	22	1.98	15	150	1022.4	75.02
Water Level Gage Station: Port Inland, MI, 9087096								
Rank	Year	Month	Day	Surge (ft)	Wind Speed (ft/s)	Wind Direction (deg, Az)	Sea Level Pressure (millibar)	Air Temperature (°F)
1	1975	1	11	3.67	57	200	N/A	16.16
2	1998	11	10	2.83	128	120	N/A	44.6
3	1985	11	20	2.43	31	260	1006.6	26.24
4	2005	11	16	2.36	37	280	N/A	41
5	1965	11	N/A	2.10	54	350	1004.6	24.08

Storm 1: Most significant event at Green Bay water level gage

Storm date: 3 – 4 December 1990

Table B2. Locations where storm produced top 20 surge levels.

Station	Surge (ft)	Station Rank
Green Bay, WI	5.41	1
Milwaukee, WI	1.78	3
Holland, MI	2.01	1

Storm track

Records indicate the storm was cyclonic and was centered over northeast Oklahoma on Dec. 3rd, over southern Lake Michigan on Dec. 4th, and over southwestern Quebec on Dec. 5th.

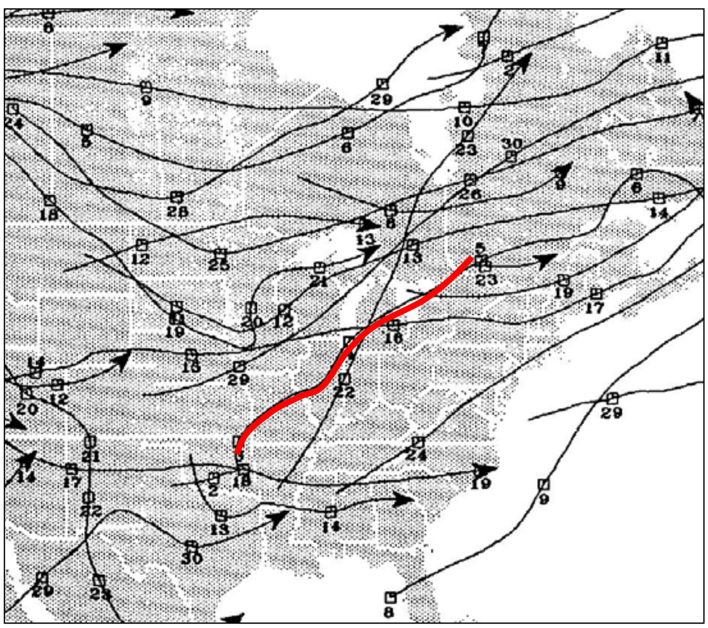


Figure B1. Storm tracks of Dec. 1990, showing Dec. 3rd-4th storm moving over Lake Michigan.

Storm summary from NOAA National Weather Service storm data

The first December snowfall in Michigan was the most intense storm of the month and season thus far. A fairly strong low-pressure system moved northeast, across Lake Michigan, late in the afternoon on Monday, December 3rd. From there, the storm moved slowly northeast, crossing northern Lake Huron during Tuesday morning, but not moving east of Lake Huron until late Tuesday afternoon. As a result, heavy snow fell in 43 of Michigan's 83 counties. Light snow began falling over southern-lower Michigan before sunrise on Monday. Snow began falling over the upper Peninsula by noon. Heavy snow with gale-force winds began blowing across most of northern-lower and upper Michigan by early afternoon. The snow ended as flurries, in most areas, by around 1500 EST on Tuesday, December 4th; however, the northwestern winds blowing across the widest part of Lake Michigan during Tuesday afternoon, caused a lake-effect snow band about 20-miles wide, remain nearly stationary from near Holland (on the Lake Michigan shoreline in northwestern Ottawa County), southeast across Battle Creek, to near Coldwater, in central Branch County. This snowbank developed early Tuesday morning and finally dissipated around 1900 EST that evening. Snowfalls in the snow band ranged from 8 to 14 inches; 11 inches on average. Over the main storm snow area, 6 to 10 inches were common across northern-lower Michigan, with two areas of 12 inches. One snow band occurred over

northeastern-lower, and the second over the Leelanau Peninsula, north of Traverse City. The upper peninsula had the most snowfall; 6 to 15 inches in most areas, with the greatest reported snowfall from Champion, (in western Marquette County) where 20 inches were reported. Due to high winds and heavy snow, considerable drifting occurred. This caused many school closings in northern-lower and upper Michigan on Tuesday. There were many reports of winds between 30 and 40 mph with frequent gusts near 50 mph. Ontonagon reported the highest gust of 64 mph. All airports in the area were closed and about 80,000 customers lost power across Michigan, during this blizzard. Four-thousand calls were made to the AAA Motor Club for road assistance; over 100 auto accidents were reported. One accident was fatal to a 56-year-old man, near Traverse City, when he crashed Tuesday morning around 1045 EST. The high winds caused some building damage near the Lake Huron shoreline. This included bricks blown off a building wall into the plate glass of the adjoining building. After all was done late on Tuesday evening, this storm will remain as one of the more memorable storms of this season.

Storm hydrographs

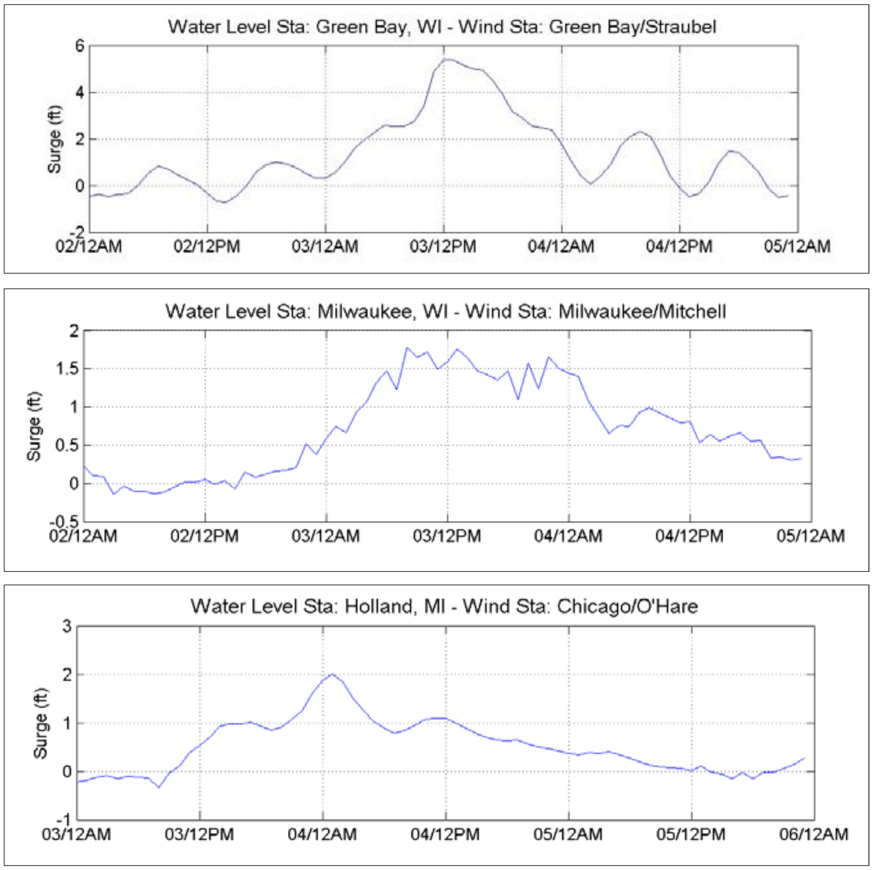


Figure B2. Surge measurements at Green Bay, Milwaukee, and Holland.

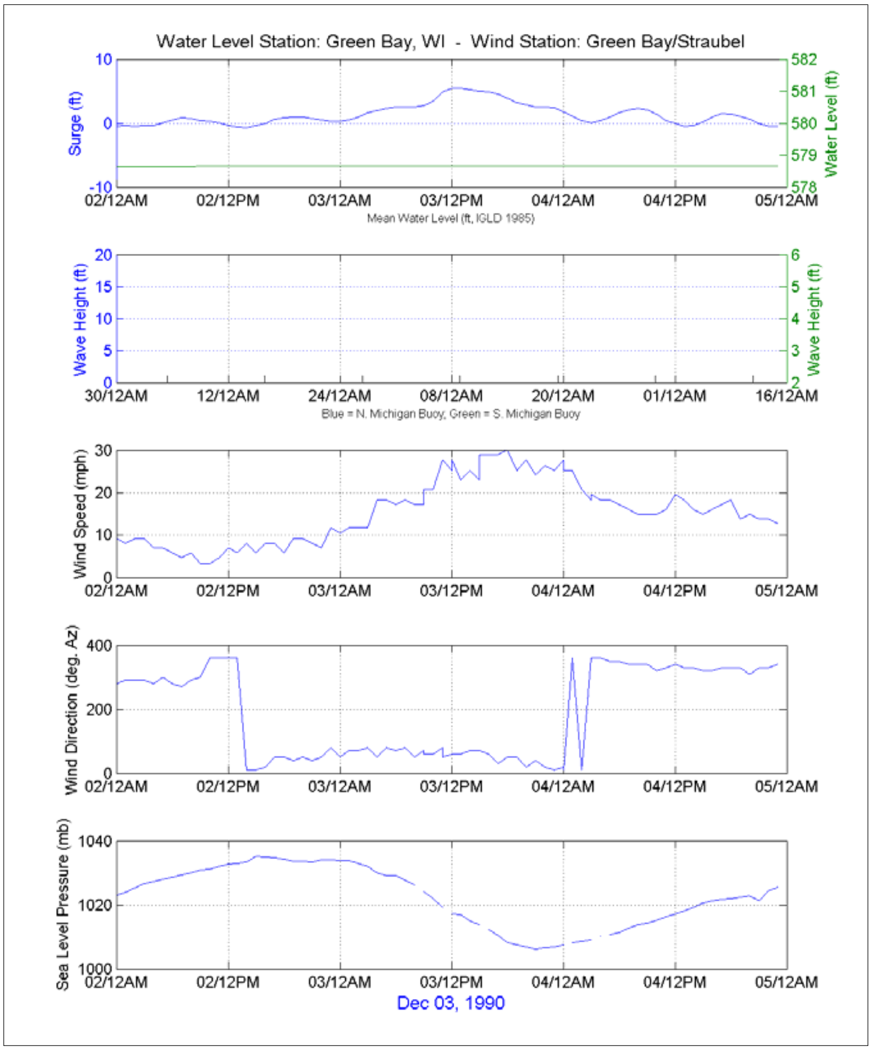


Figure B3. Surge at Green Bay and meteorological measurements at Green Bay.

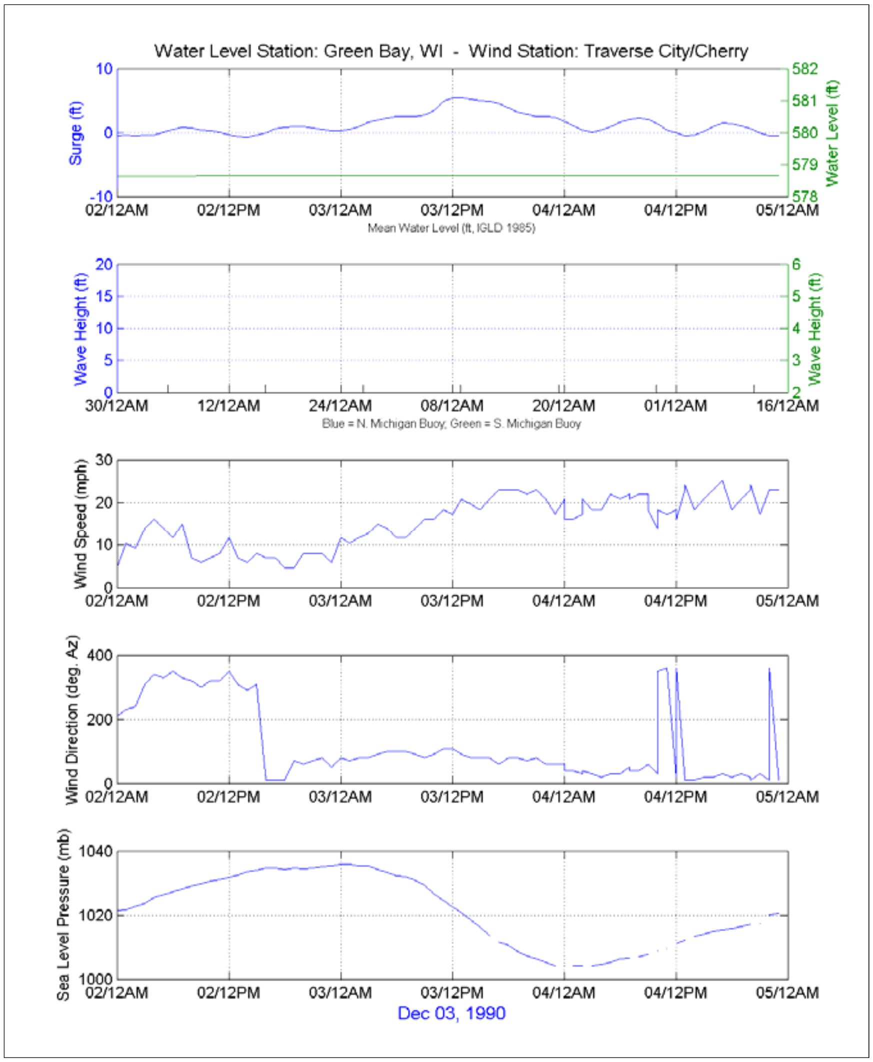


Figure B4. Surge at Green Bay and meteorological measurements at Traverse City.

Barometric pressures

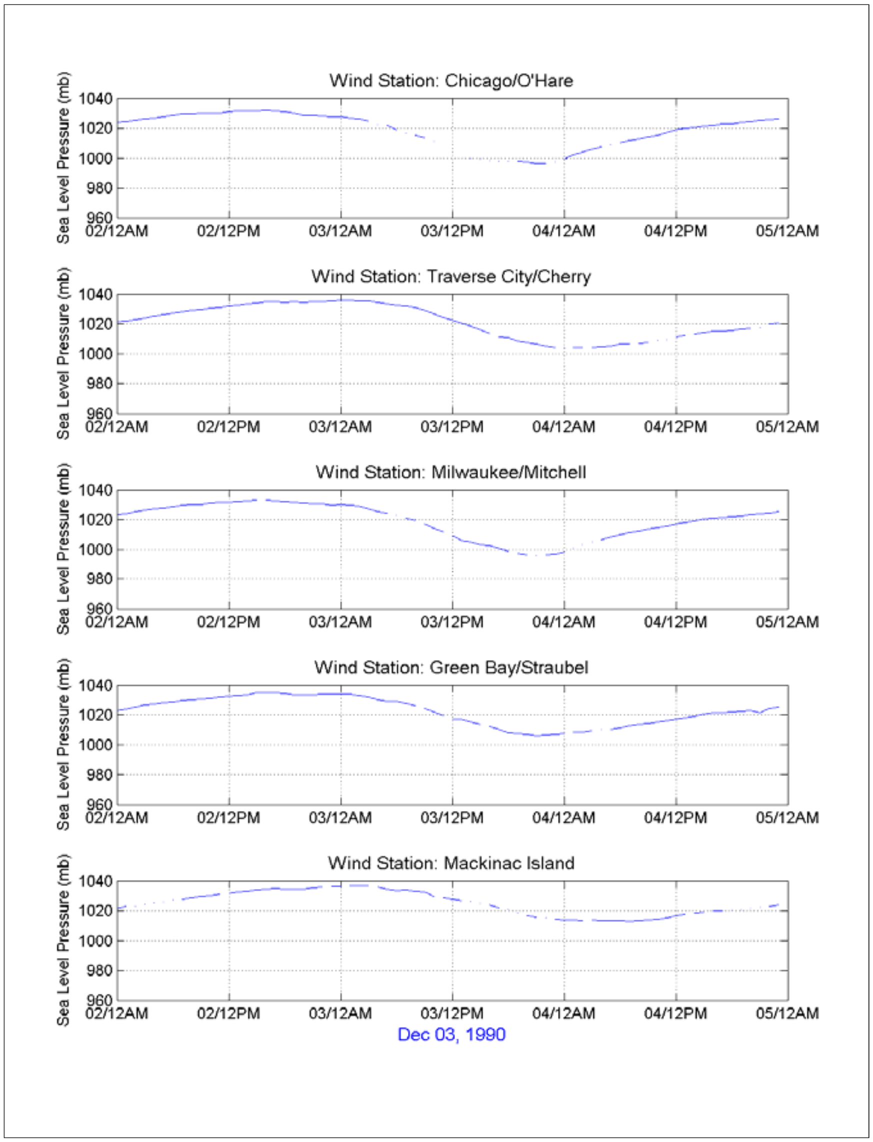


Figure B5. Atmospheric pressure at several gages.

Storm winds

Table B3. Winds during storm in knots.

Date	3-Hour Time Interval	Green Bay, WI		Milwaukee, WI		Muskegon, MI	
		Wind Spd	Wind Dir	Wind Spd	Wind Dir	Wind Spd	Wind Dir
Dec. 2, 1990	04	6	360	8	340	6	360
	07	5	010	7	340	0	000
	10	5	050	11	050	6	050
	13	7	040	13	070	8	090
	16	9	050	16	060	9	090
	19	10	080	22	060	13	070
	22	15	070	25	070	14	080
	01	18	060	30	070	20	080
Dec. 3, 1990	04	24	060	30	060	22	080
	07	20	070	27	050	23	090
	10	26	050	21	040	32	090
	13	21	040	28	030	24	100
	16	24	020	30	010	13	090
	19	16	360	22	340	9	120
	22	15	350	18	330	12	130
	01	13	340	20	320	16	340
Dec. 4, 1990	04	17	340	15	300	16	340
	07	13	320	16	310	20	320
	10	16	330	17	320	17	340
	13	12	330	13	330	16	350
	16	7	350	8	290	13	340
	19	5	280	9	270	20	340

Regional ice cover

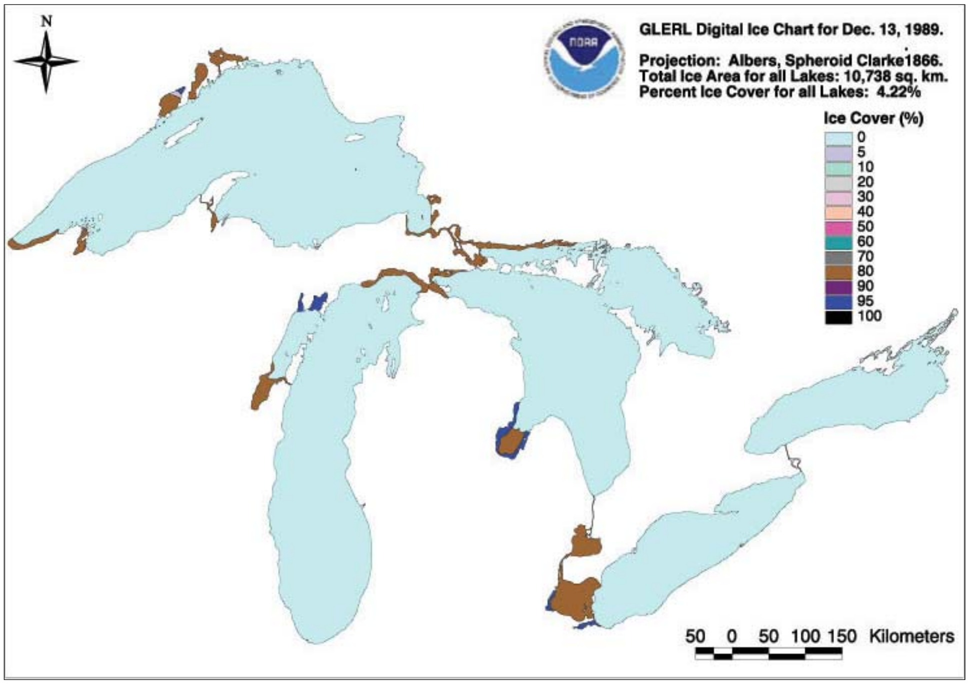
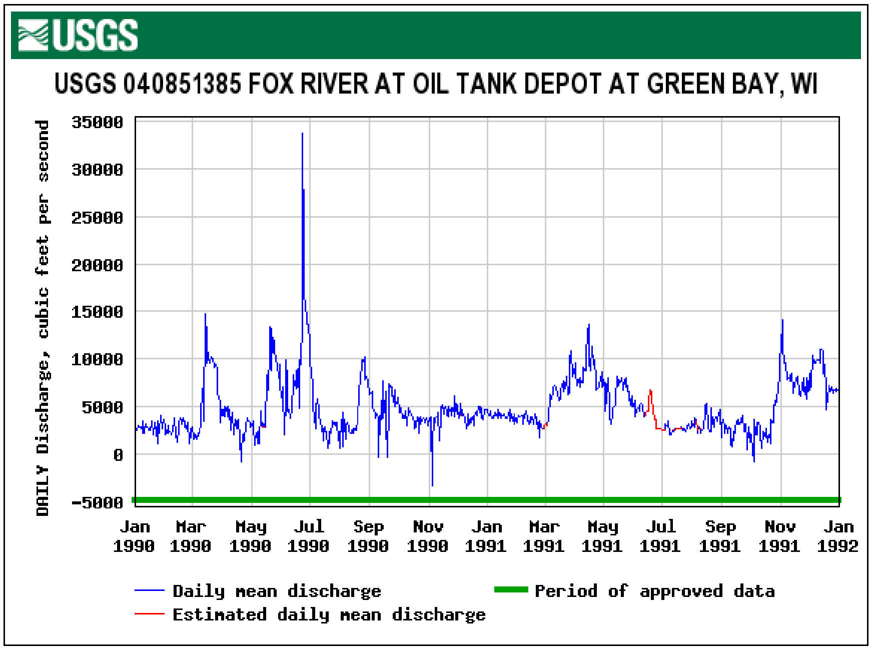


Figure B6. Regional ice cover on 13 Dec, ten days after storm.

Local hydraulic conditions

Analysis of discharge rates from a USGC river gage on the Fox River at Green Bay indicates that water level influences from snow melt and/or local precipitation do not appear to be significant for the dates of the storm.



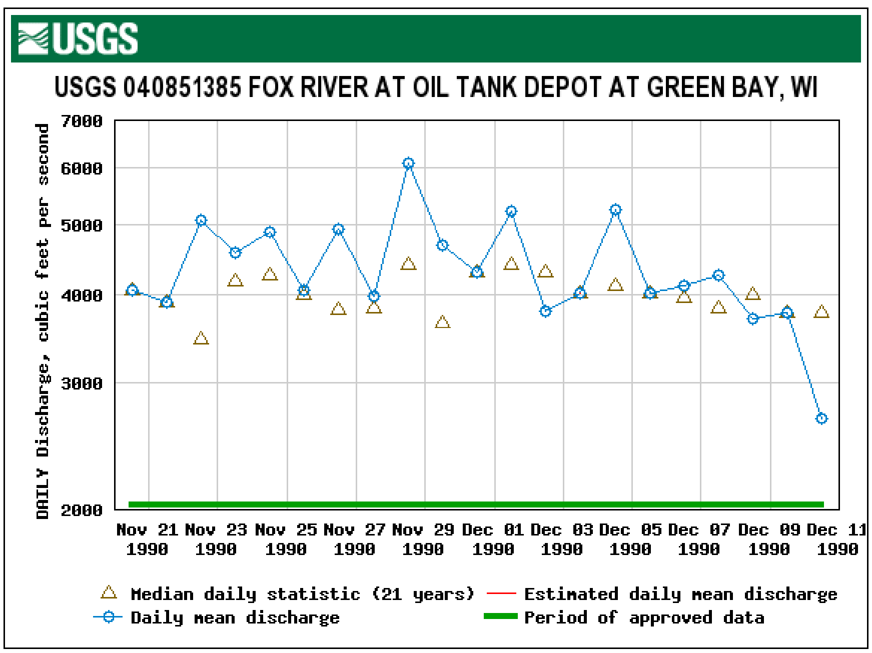


Figure B7. Local hydraulic conditions on Fox River.

Storm 2: Most significant event at Milwaukee water level gage

Storm date: 9 March 1987

The highest surge on record of 2.13 ft at Milwaukee, WI. Storm did not register a top 20 surge at any other location.

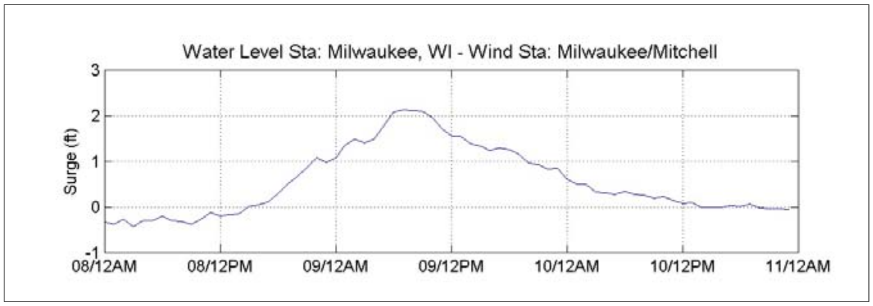


Figure B8. Surge hydrograph at Milwaukee.

Storm summary from NOAA National Weather Service storm data

Strong northeasterly winds of 35 to 45 mph and gusting to 60 mph at times whipped up waves of 8 to 15 feet along the western shore of Lake Michigan. Over one million dollars in damage resulted in Milwaukee ($800,000), Racine ($150,000), and Kenosha ($600,000) counties. In Milwaukee County, one-third of the slips at the South Shore Yacht Club were damaged. More than $500,000 worth of damage was caused to the Port of Milwaukee. Up to 4 feet of Lake Michigan shoreline was eroded and damage also took place at the Jones Island sewerage treatment plant and South Shore Park. In Racine County, extensive damage to breakwater and shoreline protective systems was reported. Large amounts of debris were tossed by the waves onto and across Pershing Drive. Land erosion in Caledonia was from 2 to 5 feet. In Kenosha County, damage included flooding of a home in Pleasant Prairie and severe damage to steel floodwalls, docks and a parking lot at Trident Marina. Waves washed away as much as 10 feet of land along 1st Avenue in the town of Pleasant Prairie.

Storm hydrographs

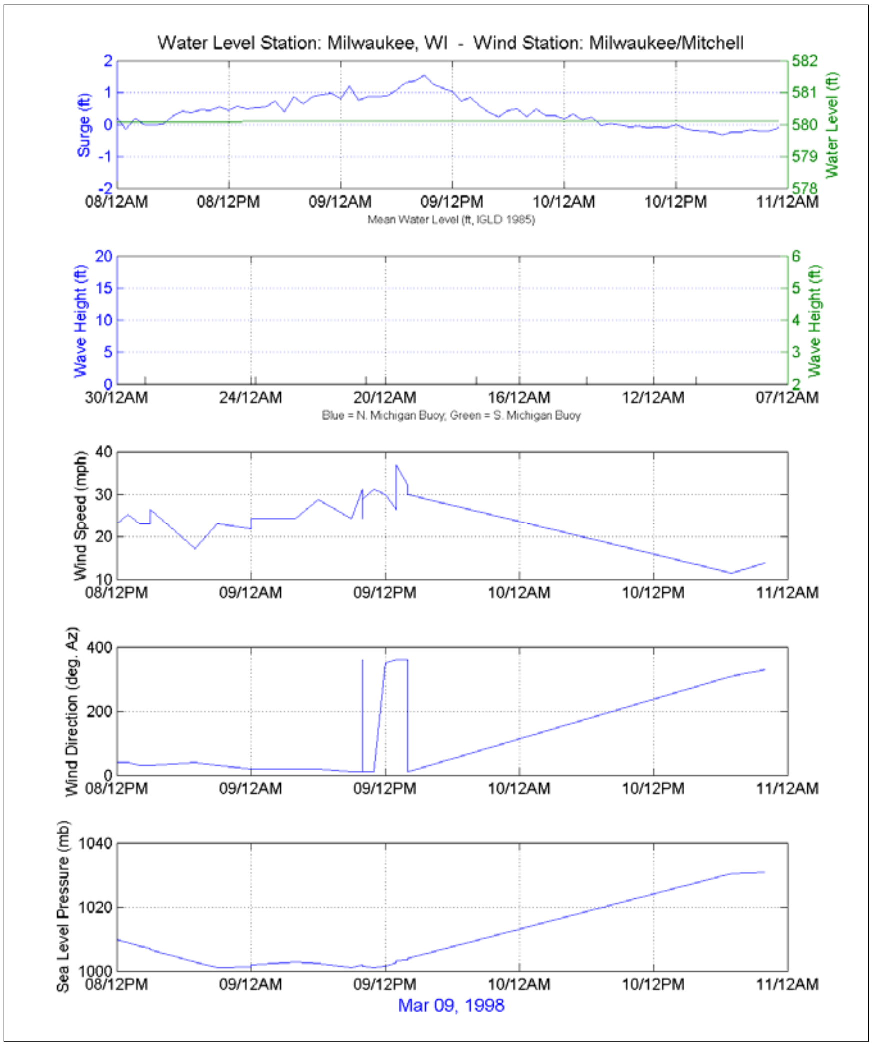


Figure B9. Surge hydrograph at Milwaukee and meteorological measurements at Milwaukee.

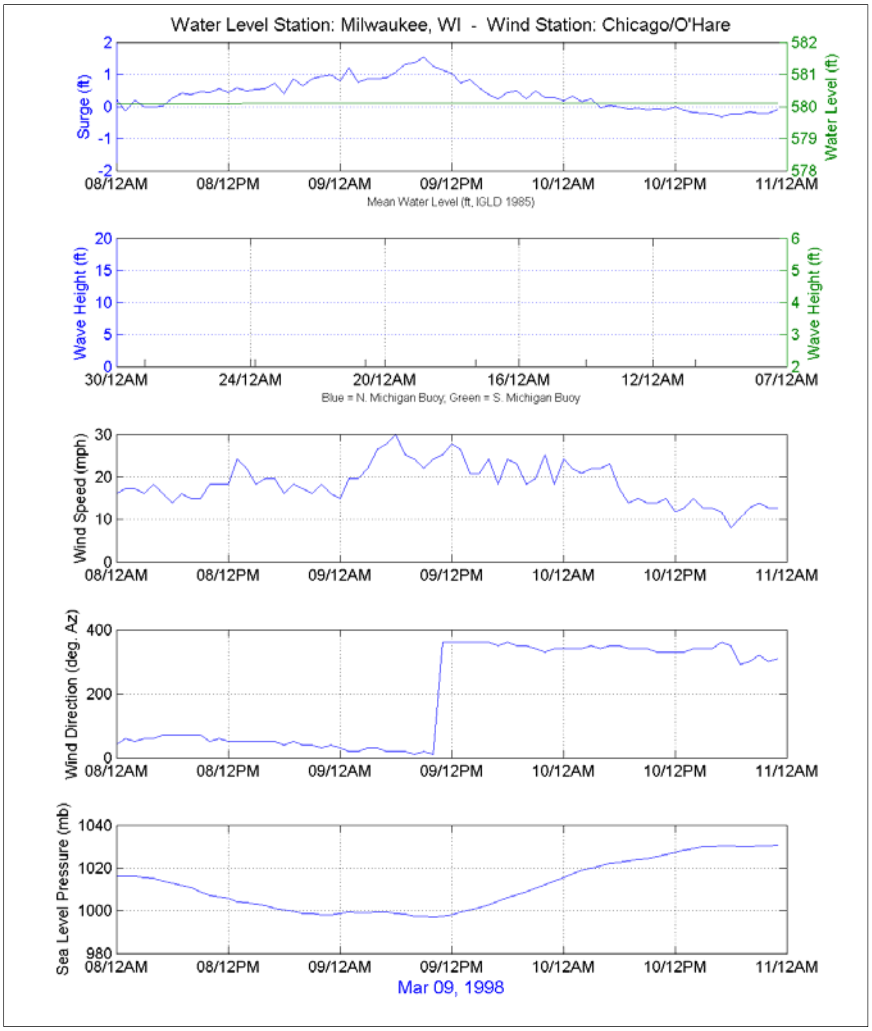


Figure B10. Surge hydrograph at Milwaukee and meteorological measurements at Chicago.

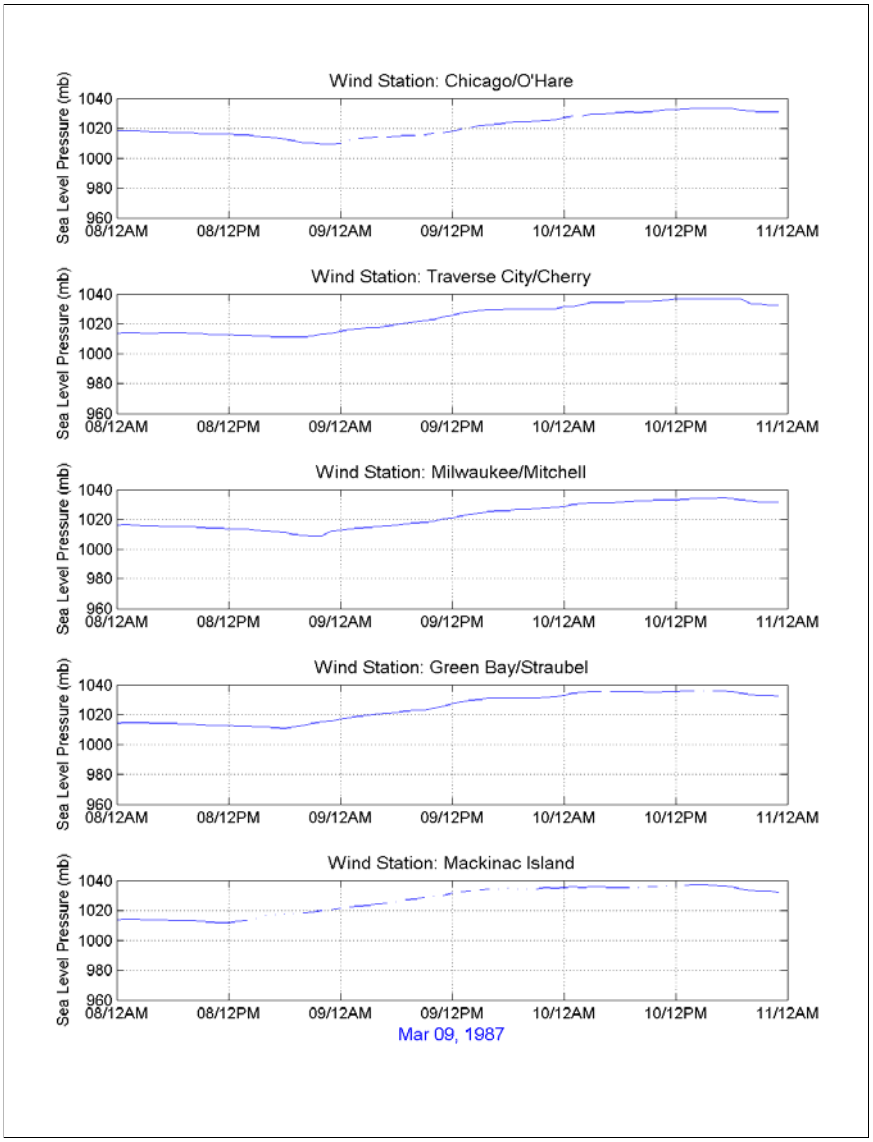


Figure B11. Atmospheric pressure measurements during storm.

Storm winds

Table B4. Winds during storm in knots.

Date	3-Hour Time Interval	Muskegon, MI		Milwaukee, WI		Chicago, IL	
		Wind Spd	Wind Dir	Wind Spd	Wind Dir	Wind Spd	Wind Dir
Mar. 8, 1987	1	10	250	6	240	6	250
	4	5	240	4	250	4	250
	7	0	0	6	260	8	270
	10	7	220	10	300	8	290
	13	7	270	9	290	7	270
	16	6	310	24	20	5	310
	19	4	320	23	20	22	20
	22	14	30	26	20	25	20
Mar. 9, 1987	1	13	20	26	30	23	10
	4	14	260	29	10	25	10
	7	15	360	26	30	27	20
	10	14	50	27	20	26	20
	13	9	60	26	20	27	20
	16	17	50	26	30	19	30
	19	13	20	21	30	23	30
	22	14	50	18	50	16	50
Mar. 10, 1987	1	12	30	14	50	17	40
	4	10	50	15	50	16	50
	7	7	50	12	70	14	50
	10	13	70	12	70	13	60
	13	13	70	10	60	12	50
	16	13	110	7	60	10	50
	19	10	100	7	60	6	340
	22	8	90	7	110	6	110

Regional ice cover

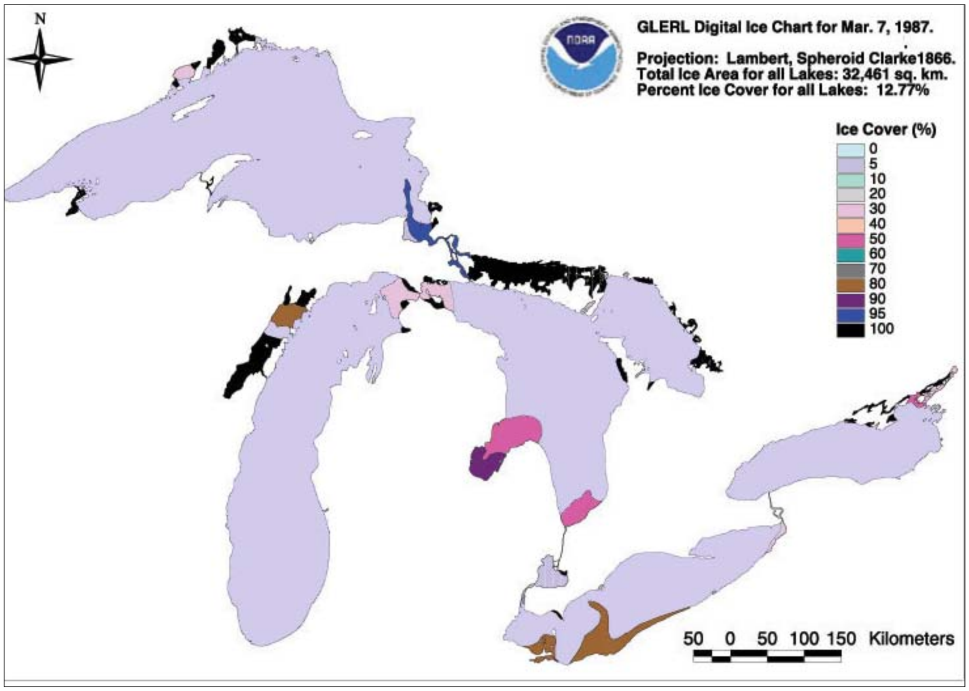


Figure B12. Regional ice cover on 7 Mar, two days before storm.

Local hydraulic conditions

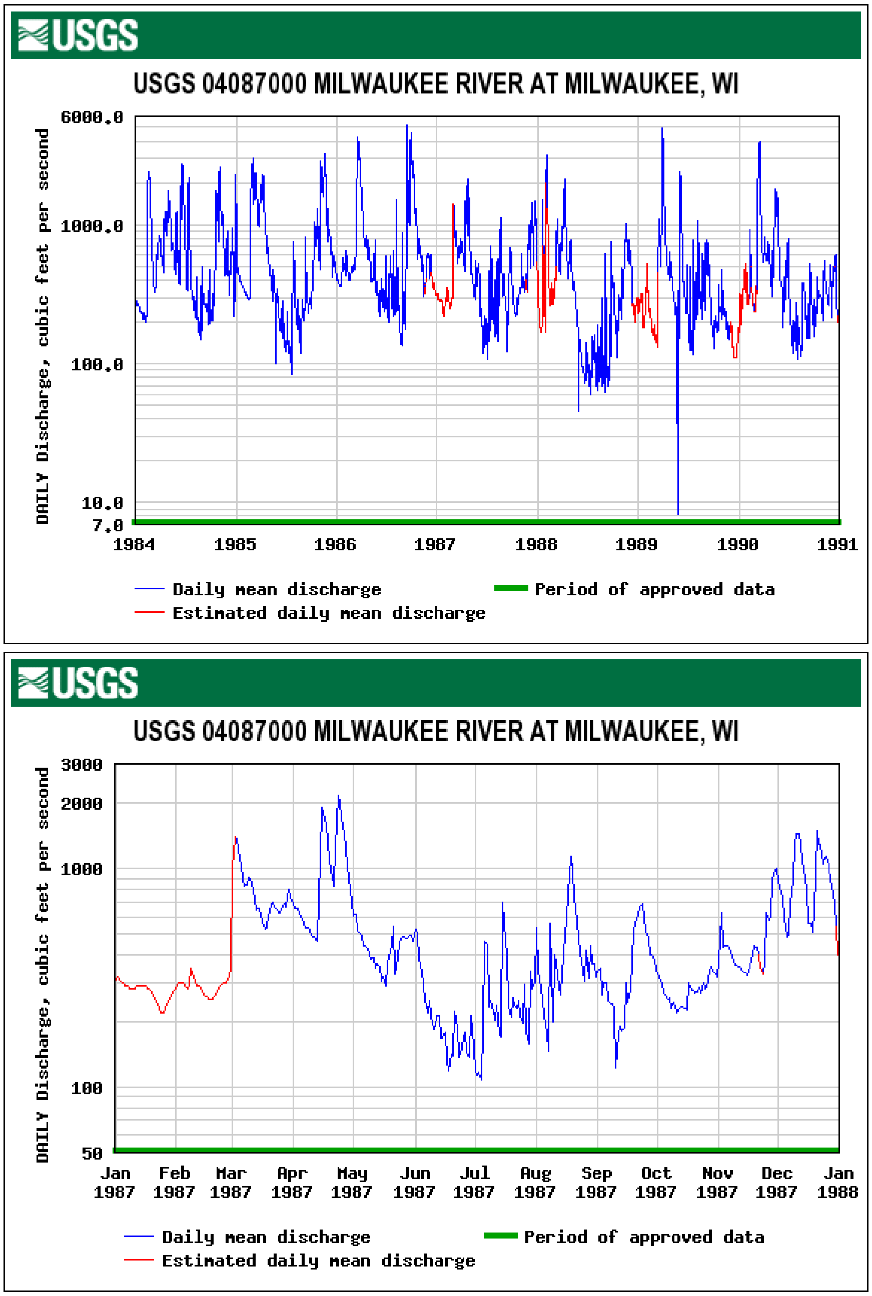
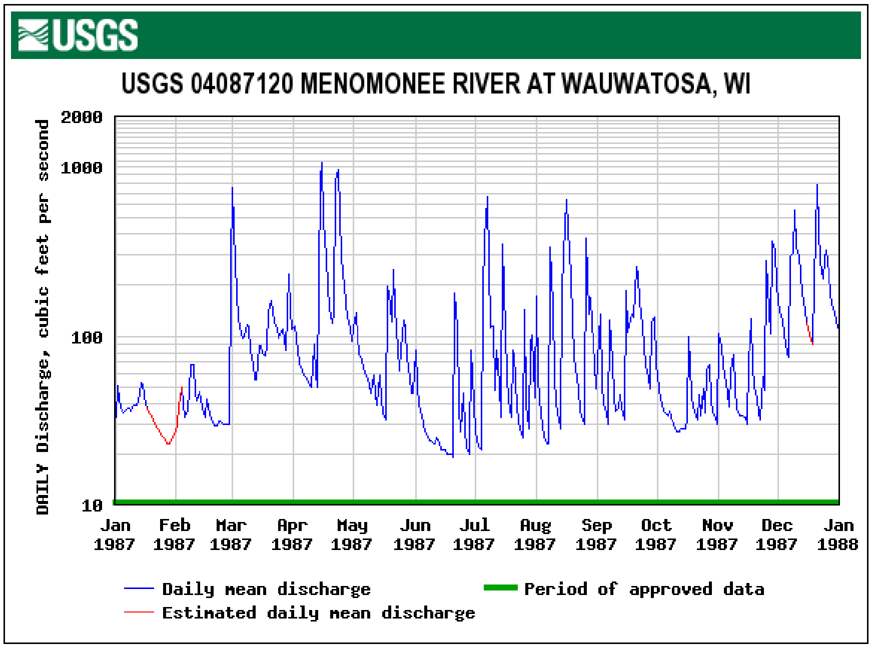


Figure B13. Local hydraulic conditions on Milwaukee River.



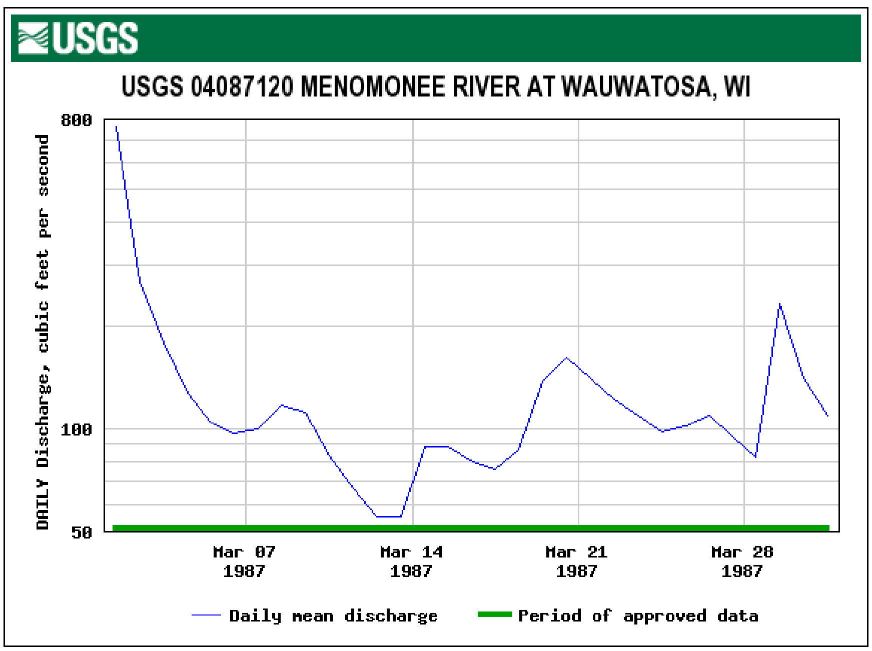


Figure B14. Local hydraulic conditions on Menomonee River.

Storm 3: Second most significant event at Port Inland water level gage

Storm date: 10 November 1998

Storm produced 2nd highest surge on record of2.83 ft at Port Inland, MI. Storm did not register a top 20 surge at any other location.

Storm track

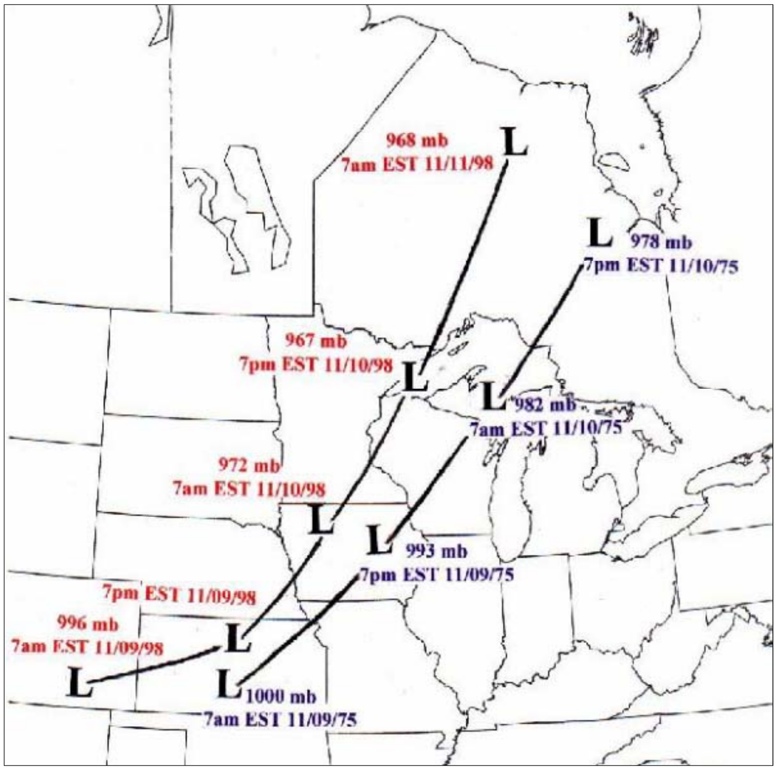


Figure B15. Storm track for subject storm in 1998 and similar event in 1975 that is famous for the sinking of the SS Edmund Fitzgerald.

Storm summary from NOAA National Weather Service storm data

Storm account for northeast Wisconsin

"An intense area of low pressure moved across the Midwest on November 10, producing very high winds, rain and snow across the region. The low, which tracked from central Iowa to western Lake Superior, resulted in record minimum pressures in Iowa and Minnesota and an unusually widespread high wind event across Wisconsin. The strong winds lasted for much of the day."

Storm account for southeast Wisconsin

"Screaming high winds raked all of south-central and southeast Wisconsin's counties for about 17 hours, resulting in widespread damage…The sustained southwesterly winds of 30 to 40 mph gusted to 60 to 70 mph, with isolated locations having gusts to around 80 mph. Preceding the powerful winds was a line of thunderstorms that dumped 1 to 2.5 inches of rain across the area.

This resulted in some urban (street and basement) and mall stream flooding in the Milwaukee to Kenosha area.

The responsible low pressure tracked from northern Kansas to north-central Iowa to near Superior in northwest Wisconsin by mid-afternoon. Due to rapid intensification, the central pressure eventually dipped to 28.43 inches (963 millibars) in Albert Lea, MN, and Austin, MN. At Madison, the pressure dropped to 28.98 inches, in Milwaukee, 28.90 inches, in Gond du Lac, 28.95 inches, and 28.87 inches in Wisconsin Dells. WSR-88D Doppler radar wind speeds registered 65 kts (75 mph) 2000 feet above ground level and 120 kts (135 mph) at 15,000 feet over the NWS Forecast Office near Sullivan in east-central Jefferson County! Interestingly, a peak gust of 76 kts (87 mph) was recorded on top of the 15-story atmospheric and Oceanic Sciences building on the UW-Wisconsin campus! This path of this low pressure was very similar to the path of an intense low pressure on November 10, 1975, whose winds generated 15 foot waves on Lake Superior, resulting the sinking of a large ore boat."

Storm account for east Michigan

"A very intense storm system moved north across the western Great Lakes on the 10th. This storm occurred on the 23rd anniversary of the sinking of the Edmund Fitzgerald in Lake Superior, and was actually very comparable to that storm, both in regards to storm intensity and storm track. The big story with both systems was the extremely strong winds that occurred. Thankfully, this storm – as opposed to the Fitzgerald storm - was forecast days in advance, and the huge majority of marine traffic on the Great Lakes sought safe harbor before wind speeds became excessive.

High winds occurred in two phases. Winds reached high wind criteria across southeast Michigan early in the afternoon of the 10th, associated with a cold front racing east across the state. A line of showers accompanied the front, locally enhancing wind speeds (see below). The strong winds slackened some during the afternoon. Wind speeds increased again in the evening, as an area of strong descent well behind the cold front allowed strong winds aloft to penetrate to ground level. The highest winds during the entire event occurred within a couple of hours of midnight. Winds diminished to below high wind criteria by dawn on the 11th."

"The extended period of strong winds caused an interesting phenomenon on Saginaw Bay. Southwest gales occurred over the waters of Saginaw Bay

for 12 to 18 hours, acting to push water out of the bay and into the main body of Lake Huron. Water levels in Saginaw Bay dropped dramatically as a result. Previous to the storm, the water level was running about 18 inches above chart datum. Any level lower than about 4 inches above chart datum begins to interfere with navigation on Saginaw Bay. At about 5:00 am on the 11th, the water level on Saginaw Bay bottomed out at an amazing 50 inches below chart datum - over five feet below the recent average! Although detailed historical records were not available for this writing, the Coast Guard in Essexville (Bay County) reported that this was the lowest water level in recent memory. Most of Saginaw Bay is quite shallow, and the removal of over five feet of water exposed a huge portion of the bay bed; some estimate that up to half of the area of the bay briefly became dry land during the storm! To illustrate this point, a pair of duck hunters were stranded on an island off of Sebewaing (Huron County), as the water level dropped too far for them to be able to boat back to the mainland. However, as the water level dropped further during the night, one of the hunters was able to walk ashore, as the intervening three miles of Saginaw Bay suddenly became dry land. As the wind slackened and swung to the west toward dawn, the water level began to rise toward a more normal level."

Storm account for north Michigan

"One of the strongest storms ever recorded in the Great Lakes crossed the region on the 10th and 11th. The storm originated over the Central Plains and lifted across western portions of Lake Superior. South to southeast winds increased steadily during the morning of the 10th and by late morning winds gusts of 40 to 50 mph were common over areas away from Lake Huron. Along the Lake Huron shoreline...winds were gusting to 60 to 70 mph with a peak gust of 95 mph reported on Mackinac Island. The wind shifted to the southwest during the afternoon...with the strongest winds generally developing along the Lake Michigan shoreline. During the afternoon and evening of the 10th wind gusts of 70 to 80 mph were common along the Lake Michigan shoreline...with 50 to 60 mph gusts across the rest of the region. Similar winds persisted into the morning of the 11th and then began to diminish during the afternoon."

Storm account for upper Michigan

"On the 23rd anniversary of the 1975 storm that sank the Edmond Fitzgerald on Lake Superior, a deep low pressure system (central pressure 28.41 inches of mercury) developed over the central plains and tracked northeast across

western Lake Superior. Strong winds spread over Michigan's Upper Peninsula with sustained speeds of 30 to 40 mph and gusts as high as 87 mph. A gust of 94 mph was recorded by the Ontonagon County Road Commission....Beach erosion due to 8 to 15 foot waves was reported along the western Lake Superior shoreline and on the north shore of Lake Michigan. The U.S. Forest Service reported that at least 10 million dollars worth of timber was lost in the Ottawa and Hiawatha National Forests."

Storm hydrographs

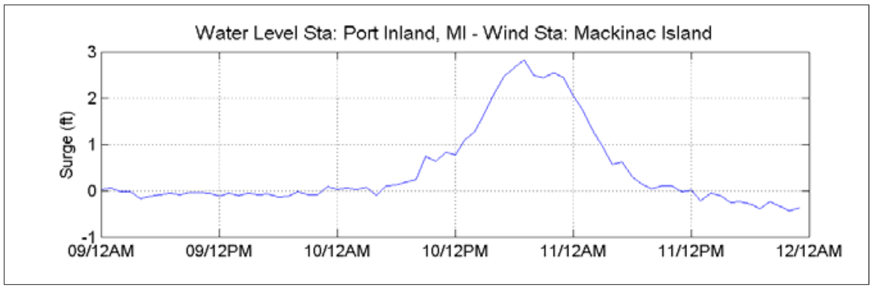


Figure B16. Surge hydrograph at Port Inland.

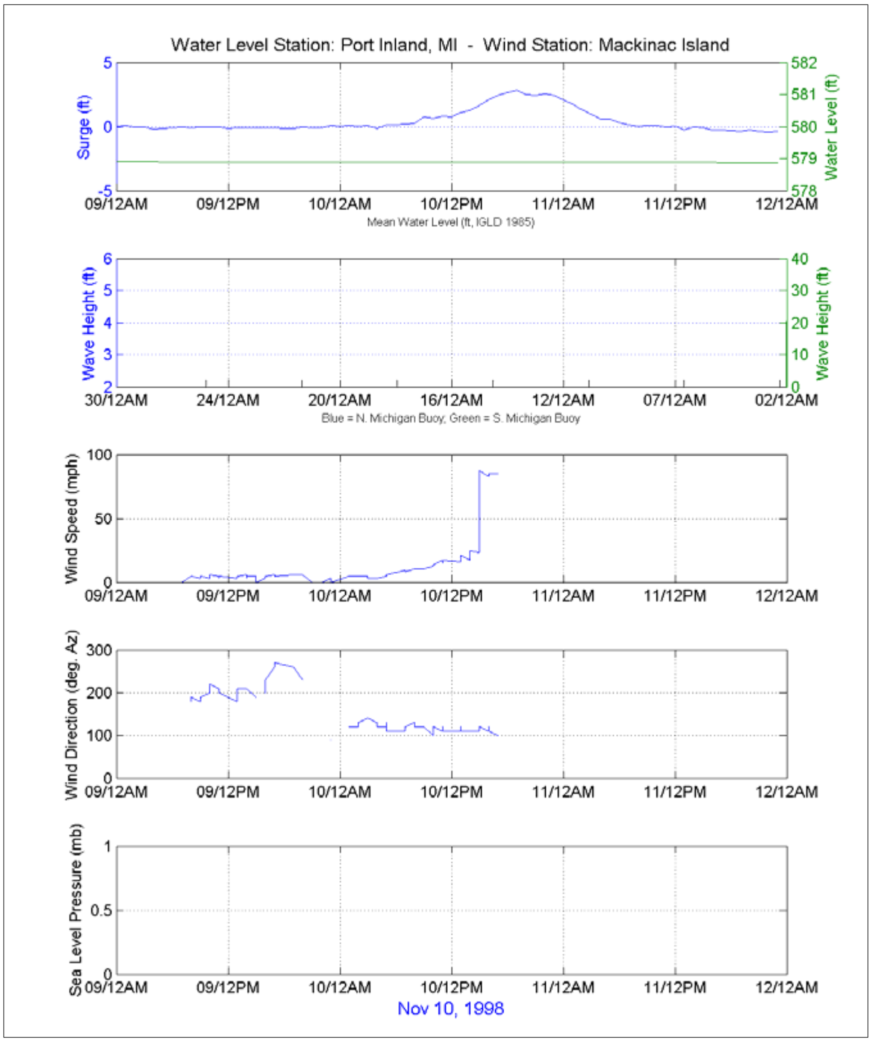


Figure B17. Surge at Port Inland and meteorological conditions at Mackinac Island.

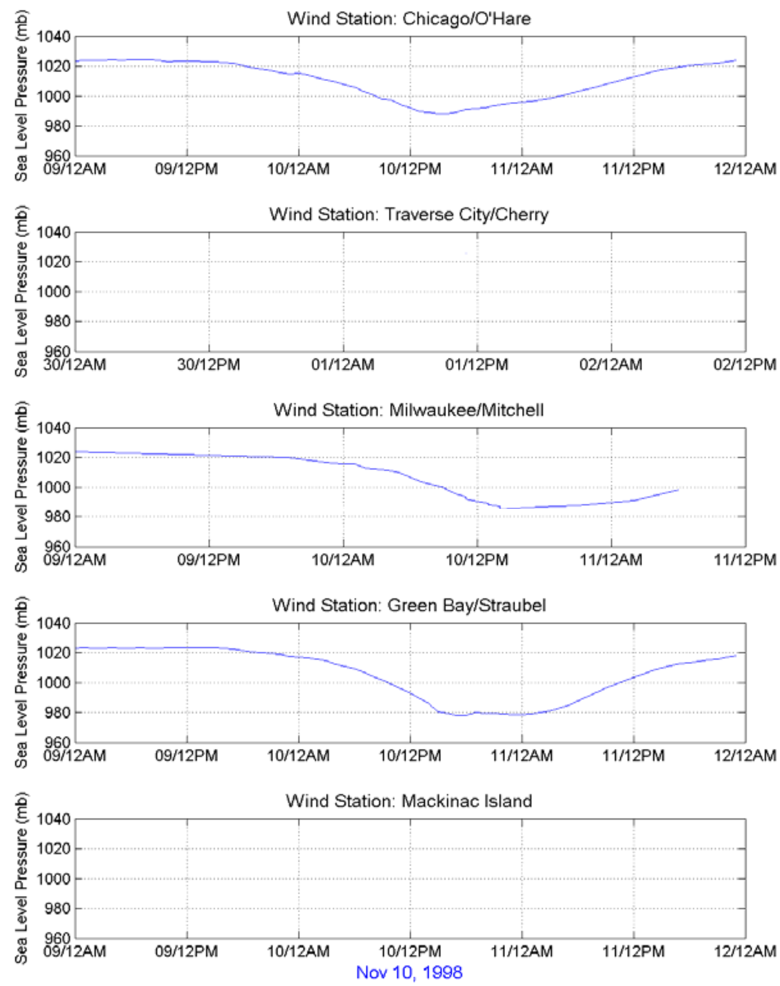


Figure B18. Atmospheric pressure measurements during storm.

Storm wind and atmospheric pressure

Table B5. Winds in mph and atmospheric in in., Hg, during storm.

Date	3-Hour Time Interval	Muskegon, MI			Green Bay, WI			Sault Ste. Marie, MI		
		Wind Spd	Wind Dir	SL Pressure	Wind Spd	Wind Dir	SL Pressure	Wind Spd	Wind Dir	SL Pressure
Nov. 9, 1998	1	6	140	30.22	6	270	30.21	0	0	30.17
	4	3	140	30.22	5	260	30.22	0	0	30.17
	7	6	130	30.22	3	200	30.22	3	150	30.17
	10	3	80	30.23	5	170	30.17	0	0	30.19
	13	9	160	30.19	12	150	30.1	3	180	30.14
	16	10	120	30.12	7	90	30.04	0	0	30.14
	19	10	110	30.07	13	130	29.96	5	150	30.13
	22	14	100	30	15	100	29.81	5	110	30.11
Nov. 10, 1998	1	16	110	29.86	17	100	29.58	6	110	30.05
	4	20	120	29.66	20	130	29.32	13	110	29.93
	7	15	130	29.48	29	140	28.95	16	120	29.77
	10	21	140	29.25	32	200	28.89	22	120	29.57
	13	28	180	29.16	32	210	28.92	17	130	29.28
	16	41	210	29.24	35	210	28.9	18	140	28.96
	19	44	220	29.31	30	220	28.97	31	220	29.02
	22	38	220	29.36	31	240	29.17	36	200	28.99
Nov. 11, 1998	1	43	220	29.48	22	250	29.42	22	200	28.96
	4	44	220	29.62	22	260	29.63	16	240	29.03
	7	37	260	29.79	22	260	29.82	21	250	29.23
	10	33	260	29.93	20	280	29.92	23	270	29.46
	13	37	270	30.05	20	240	30	24	280	29.62
	16	23	260	30.13	8	240	30.1	24	260	29.76
	19	23	220	30.19	13	240	30.16	17	260	29.86
	22	23	220	30.26	12	240	30.19	21	270	29.93

Regional ice cover

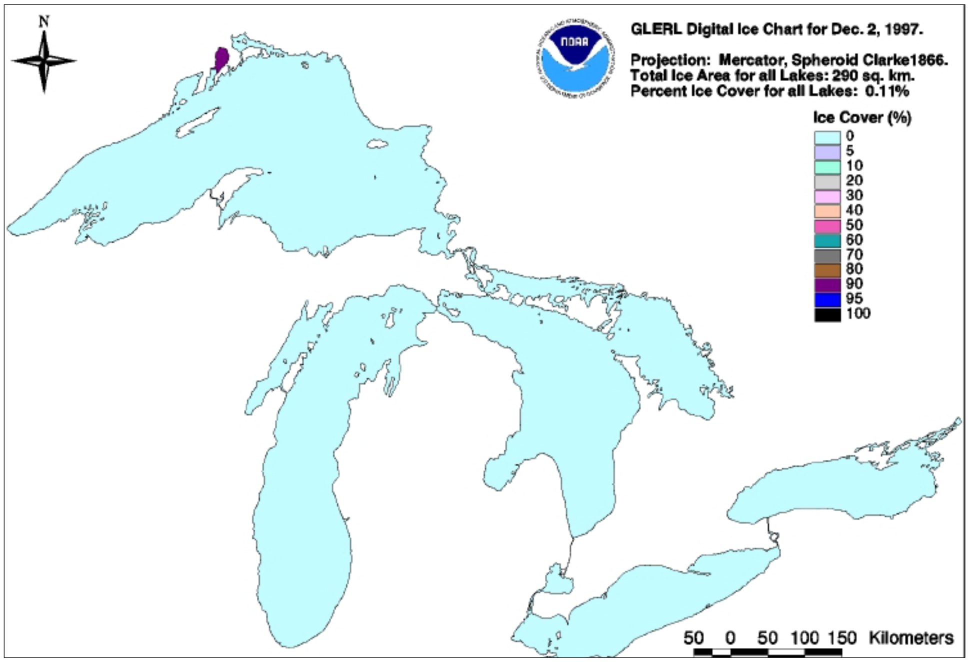


Figure B19. Regional ice cover nearly 1 month after storm. This was the earliest ice data plot available during 1998.

Storm 4: Most significant event at Kewaunee water level gage

Storm date: 4 September 1990

Highest Surge on record at Kewaunee, WI – 2.45 ft

Storm summary from NOAA National Weather Service storm data

Nothing of record to indicate this water level reading resulted from storm activity. No entries for any storm events (thunderstorms, wind storms, or tornadoes) on September 4th in Wisconsin.

Storm hydrographs

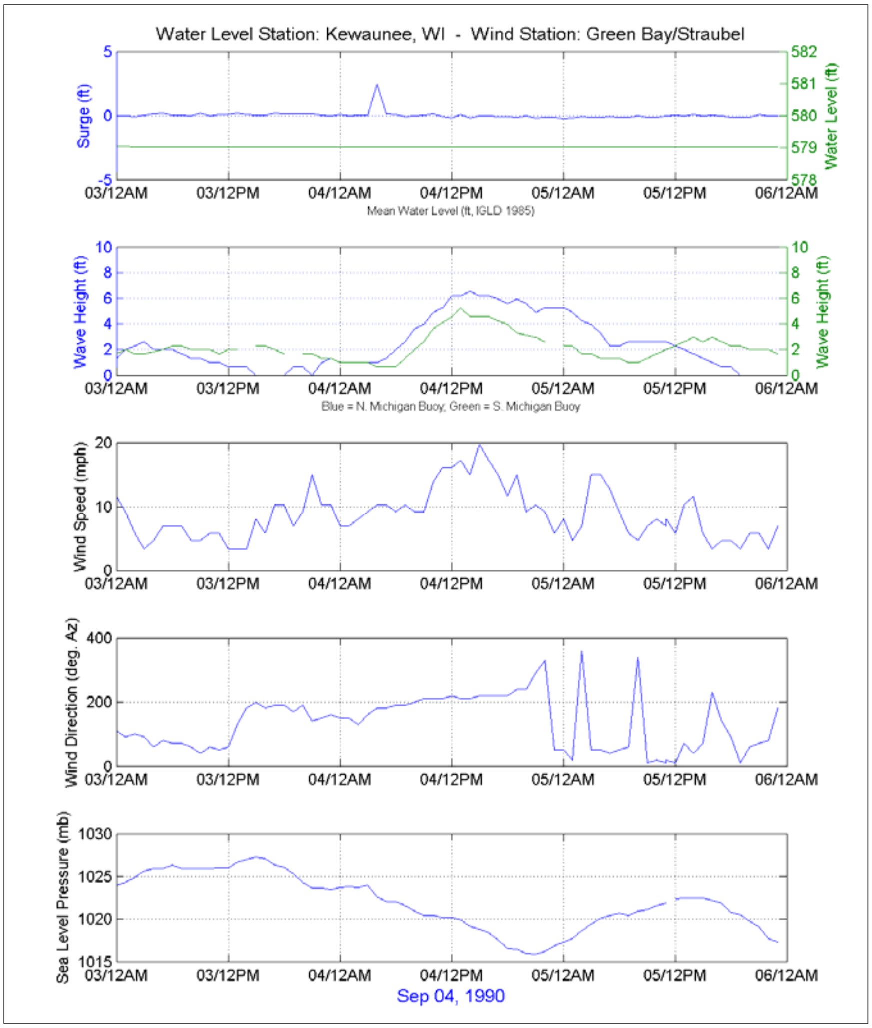


Figure B20. Surge hydrograph at Kewaunee and meteorological data at Green Bay.

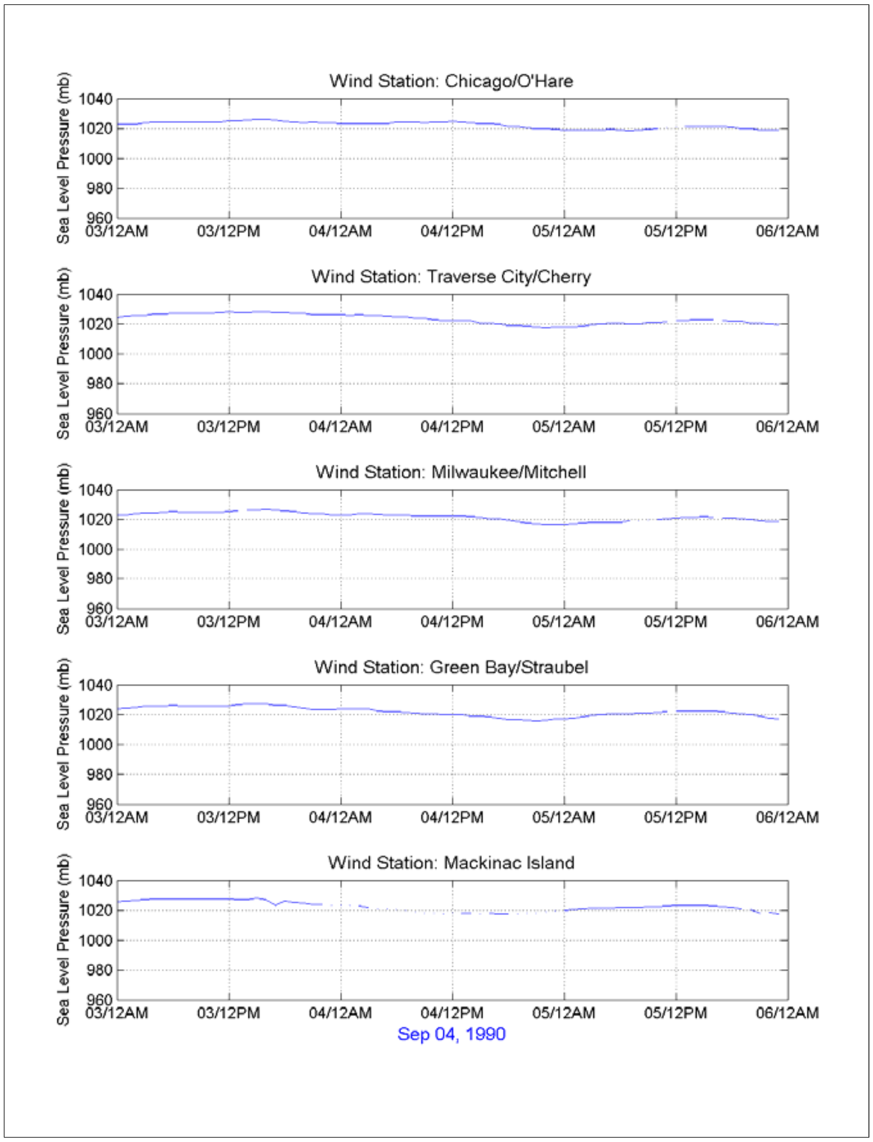
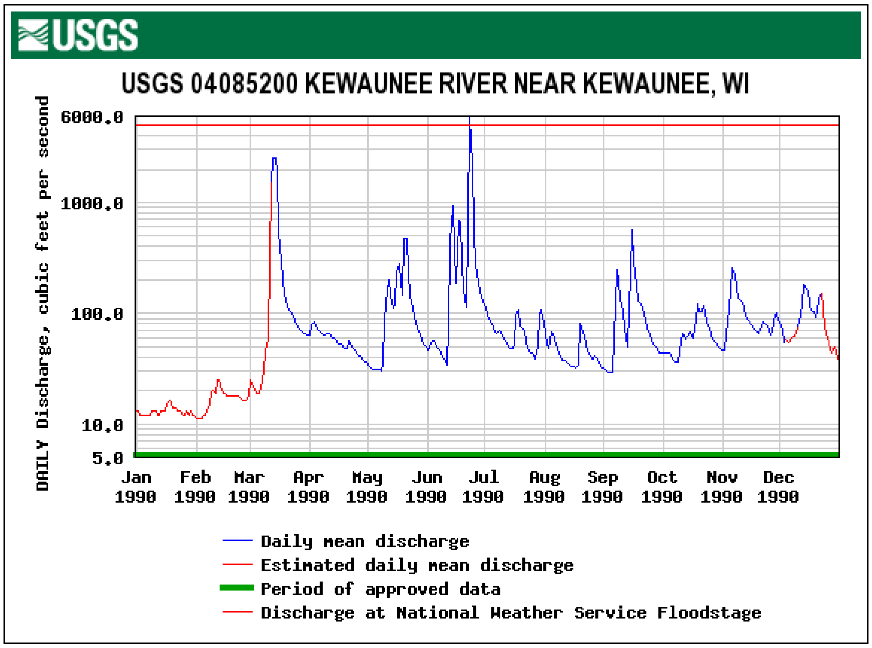


Figure B21. Atmospheric pressure measurements during storm.

USGS hydraulic conditions

Stream gage readings near Kewaunee for September 1990 show levels well below flood stage.



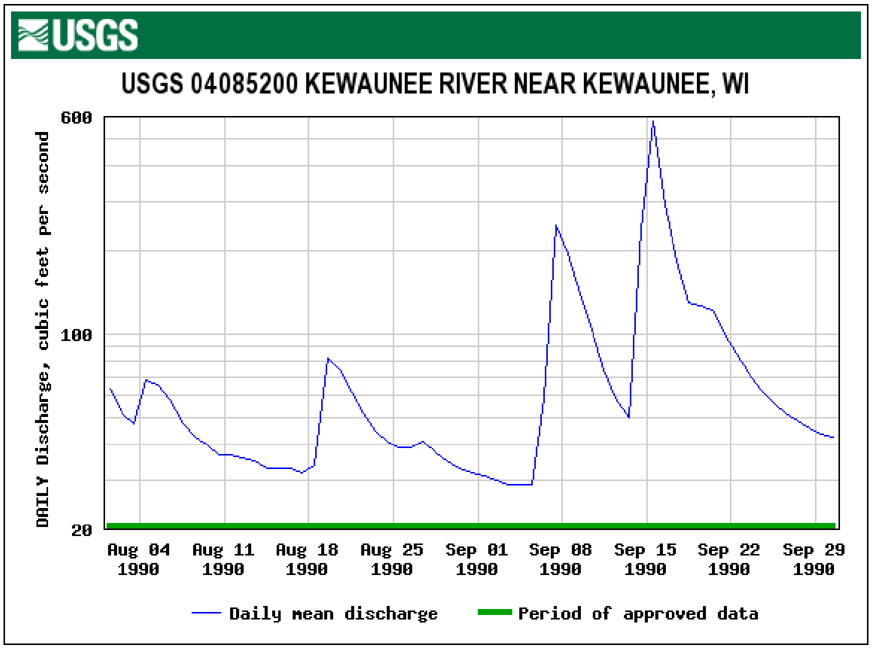


Figure B22. Local hydraulic conditions on Kewaunee River.

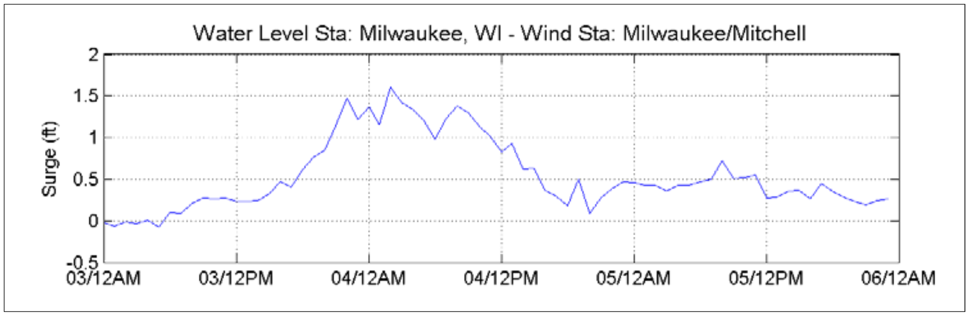
Storm 5: Significant event at large number of water level gages

Storm Date: 4 March 1985

Table B6. Locations where storm produced top 20 surge levels.

Station	Surge (ft)	Station Rank
Ludington, MI	1.32	3
Milwaukee, WI	1.61	4
Kewaunee, WI	1.26	7
Port Inland, MI	1.67	14
Sturgeon Bay Canal, WI	1.34	17

Storm hydrographs



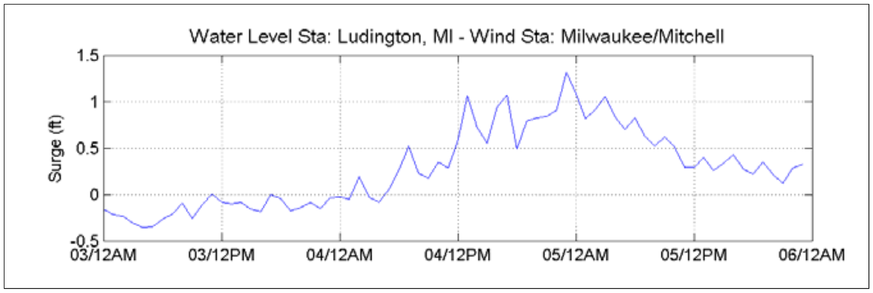


Figure B23. Surge hydrographs during storm at Milwaukee and Ludington.

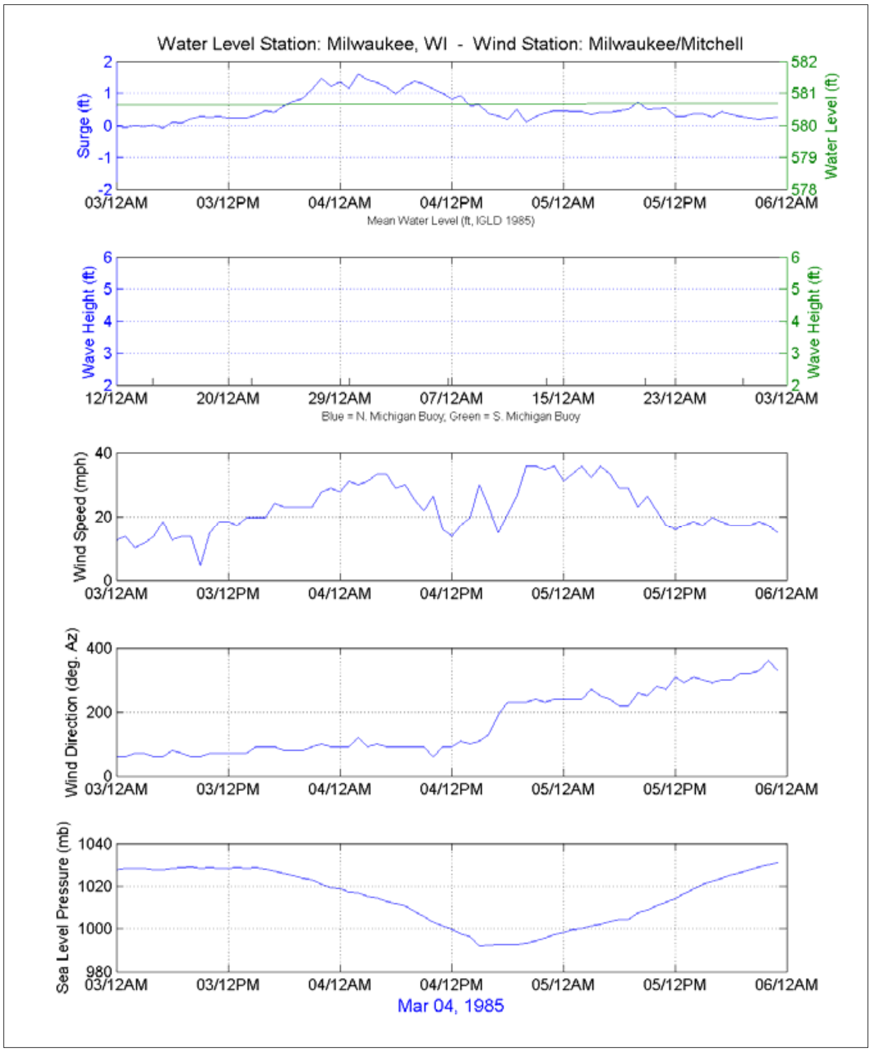


Figure B24. Surge hydrograph at Milwaukee and meteorological measurements at Milwaukee.

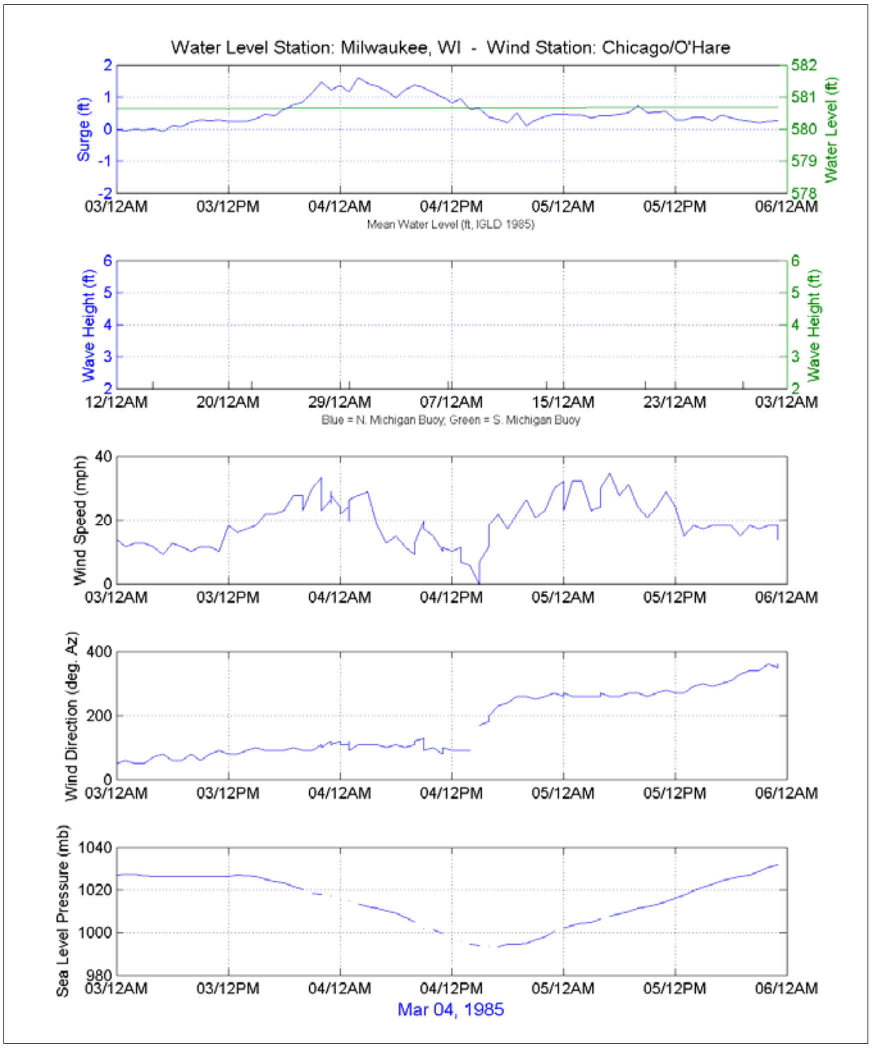


Figure B25. Surge hydrograph at Milwaukee and meteorological measurements at Chicago.

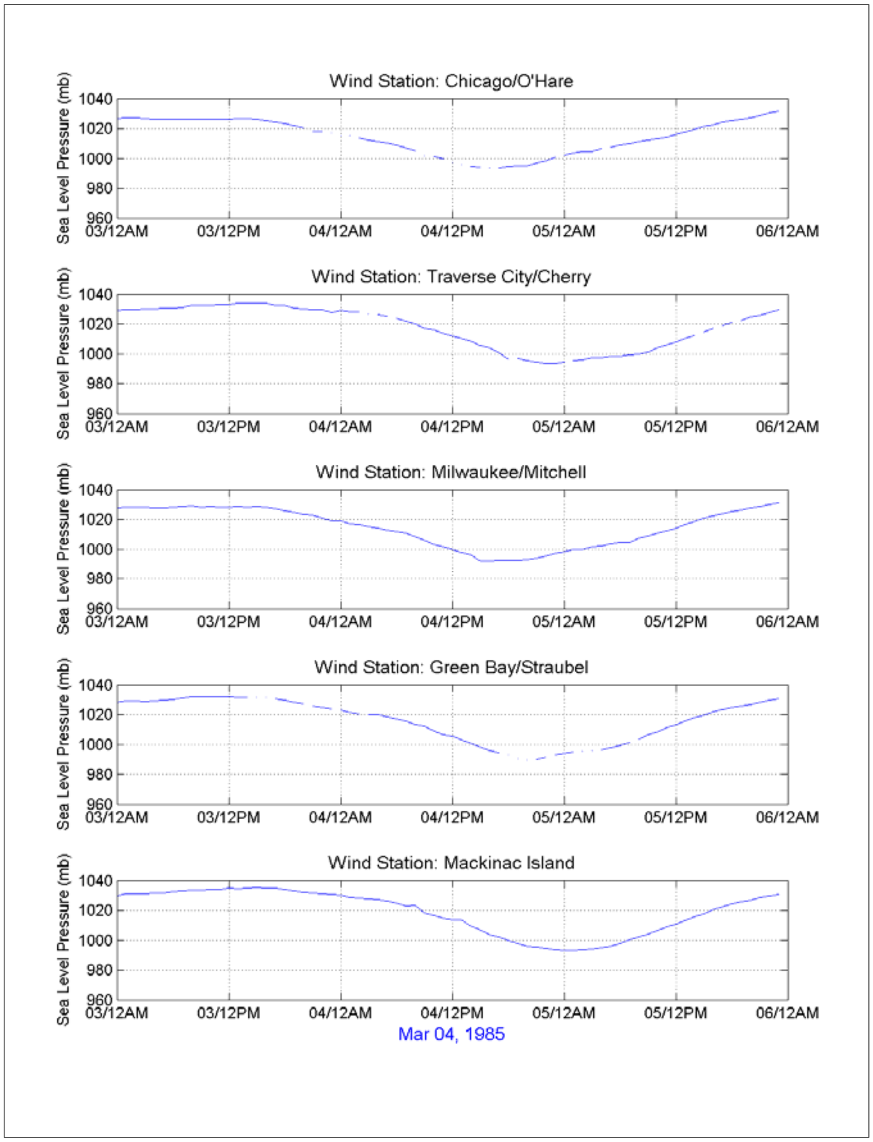


Figure B26. Atmospheric pressure measurements during storm.

Storm summary from NOAA National Weather Service storm data

Storm summary for Wisconsin

A major winter storm brought a variety of severe winter weather conditions to all portions of the state. Over northwest Wisconsin between 10 and 19

widespread power outages occurring. The strong winds blowing off of Lake Michigan produced waves and ice which tore out large sections of a sea wall near Milwaukee's Summerfest grounds,causing $230,000 damage to the festival grounds. Other damage along the western shore of Lake Michigan included

$200,000 damage to the Smith Brothers parking lot, restaurant and hotel in Port Washington, when 15 foot waves crashed onshore. Across the state numerous

Storm summary for Michigan

Lower Peninsula. Winds were measured up to 73mph at Ontonagon, 75mph at Houghton, 60mph at the Mackinac Bridge, and 57mph at Harbor Beach. 5 persons were injured in the collapse of a factory The Mackinac Bridge closed for 4 hours due to wind and low visibility. Strong northeast winds caused flooding and ice damage to shore installations on Lake St. Clair and Lake Erie. The water level at Gibraltar reached 80 inches above chart datum. Many roads flooded in eastern Monroe and southeastern Wayne Counties. 100 families evacuated.

Storm winds

Table B7. Winds during storm in knots.

Date	3-Hour Time Interval	Muskegon, MI		Milwaukee, WI		Chicago, IL	
		Wind Spd	Wind Dir	Wind Spd	Wind Dir	Wind Spd	Wind Dir
Mar. 4, 1985	1	7	70	4	60	10	60
	4	11	80	16	70	16	80
	7	15	70	17	90	16	100
	10	15	90	20	80	20	90
	13	17	110	20	90	26	90
	16	20	100	24	90	20	110
	19	26	100	27	90	25	110
	22	26	110	25	90	13	110
Mar. 5, 1985	1	28	100	19	90	17	130
	4	28	90	12	90	9	90
	7	23	110	26	110	0	0
	10	12	90	18	230	15	240
	13	10	120	31	240	18	250
	16	16	240	27	240	20	270
	19	24	260	28	270	20	260
	22	24	250	25	220	24	260
Mar. 6, 1985	1	28	250	23	250	18	260
	4	24	260	14	310	21	270
	7	22	290	15	300	15	300
	10	20	310	15	300	16	310
	13	15	320	16	330	15	340
	16	19	330	9	310	13	350
	19	11	360	7	290	7	330
	22	6	360	7	290	5	320

Regional ice cover

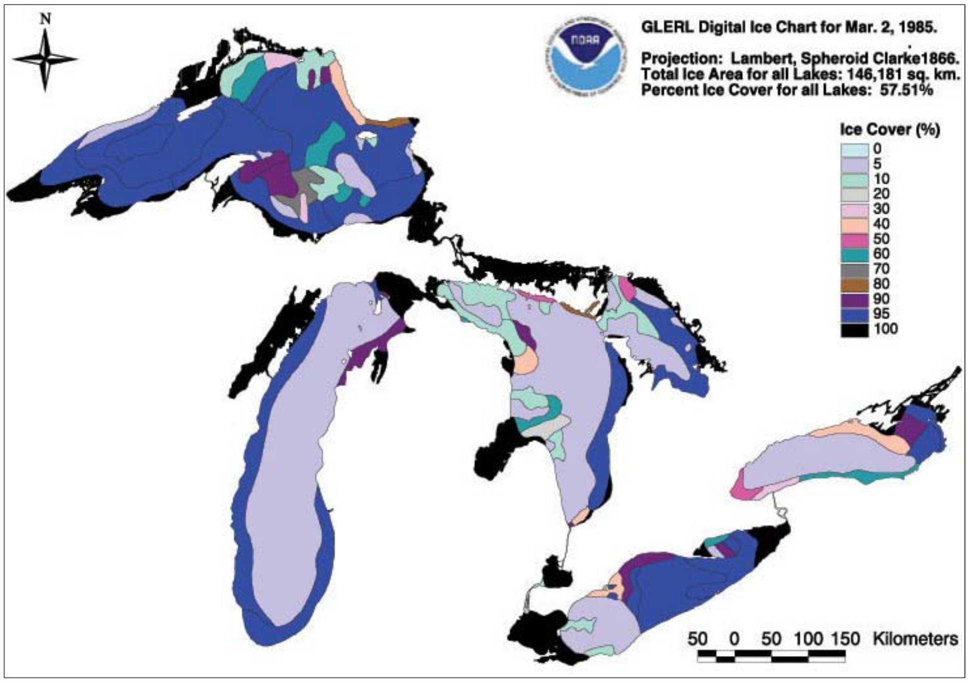
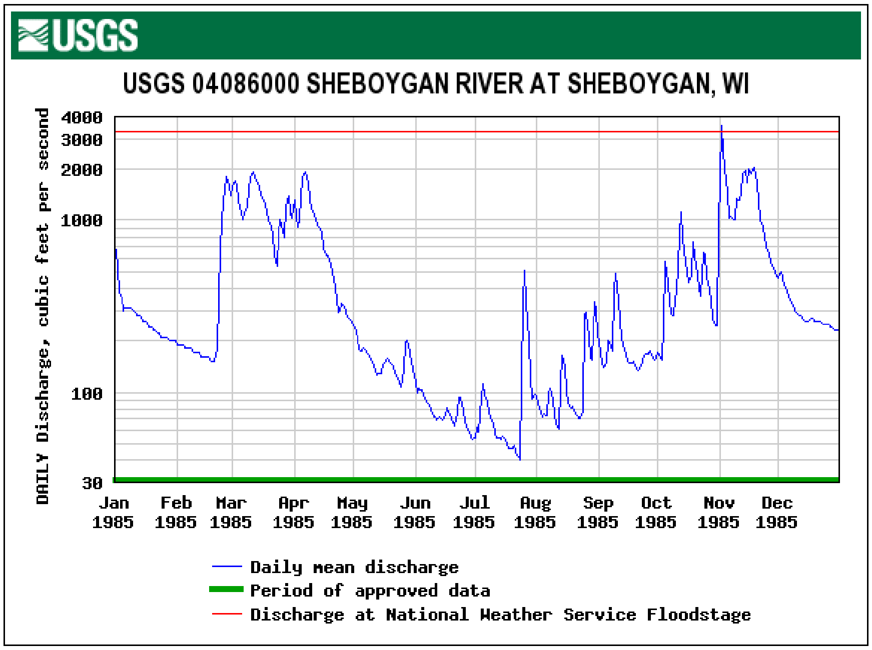


Figure B27. Local hydraulic conditions on Sheboygan River.

Local hydraulic conditions



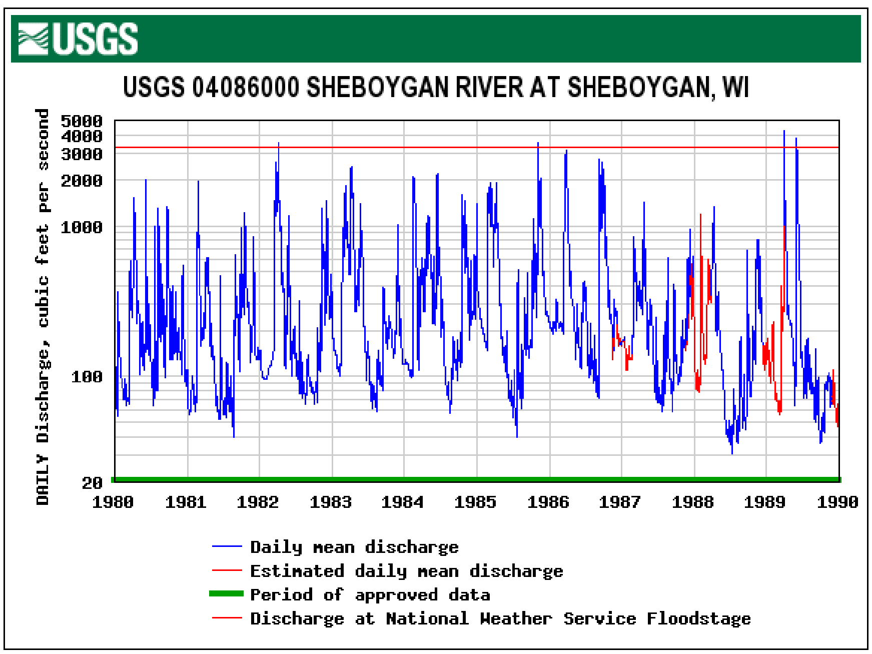
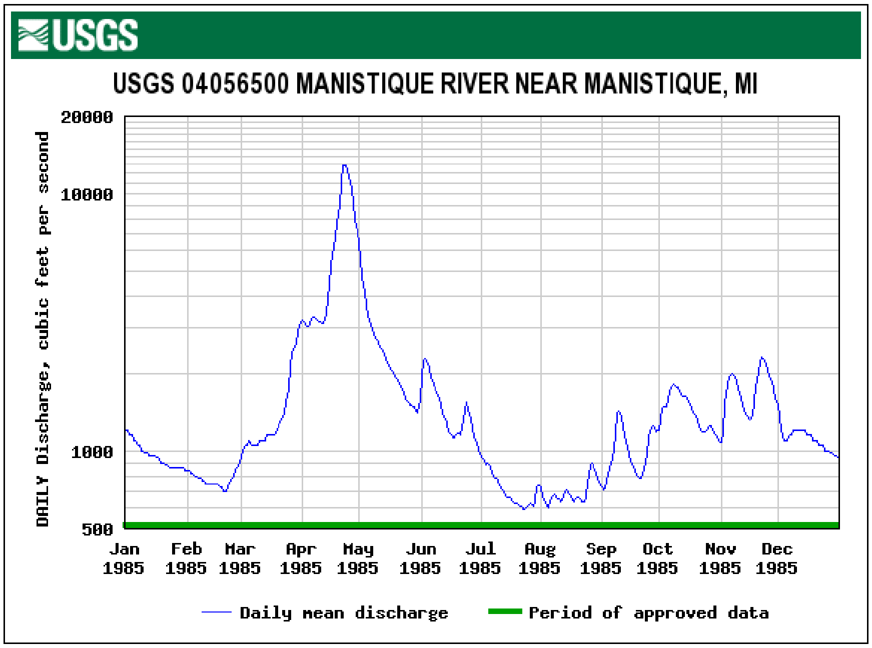


Figure B28. Local hydraulic conditions on Sheboygan River.



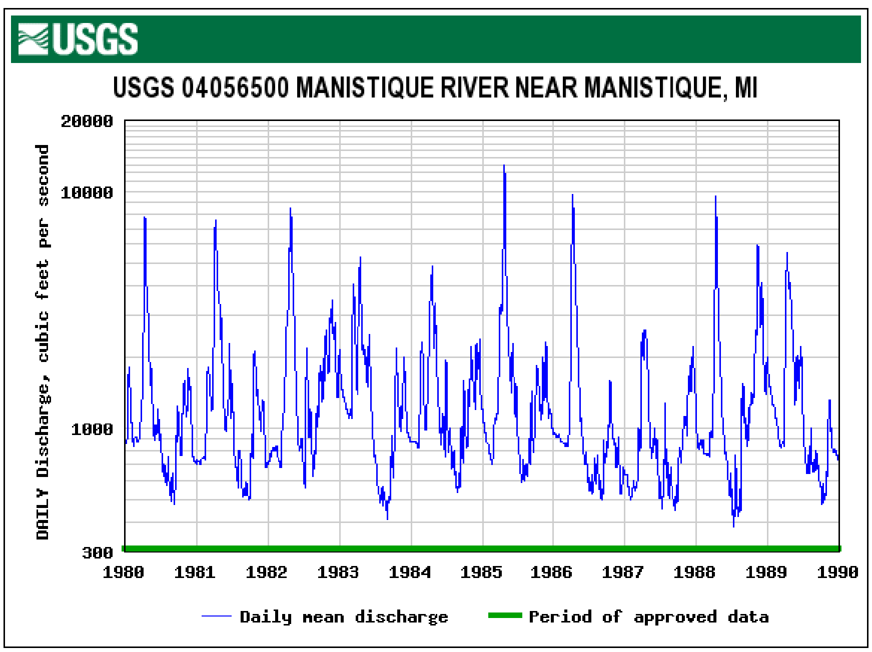


Figure B29. Local hydraulic conditions on Manistique River.

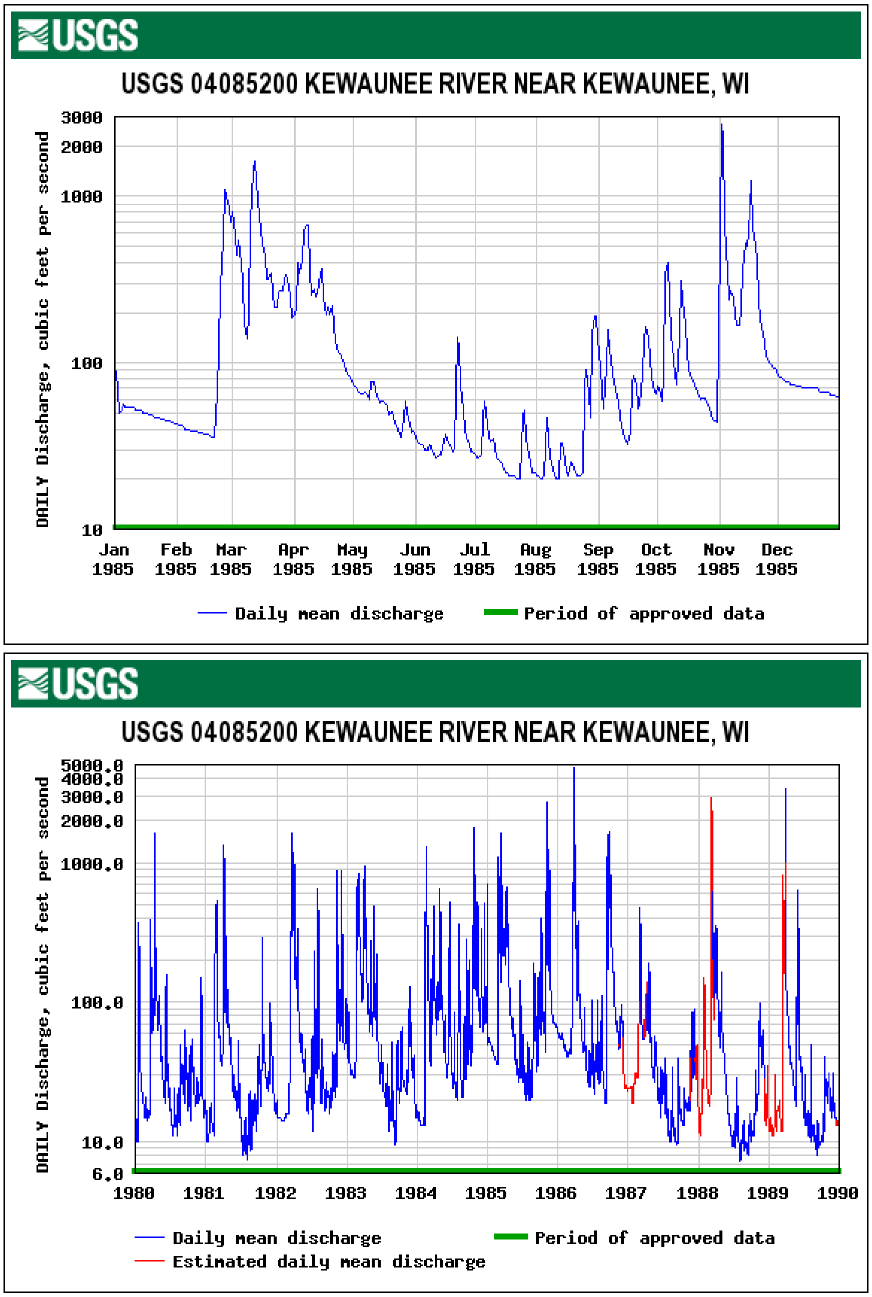


Figure B30. Local hydraulic conditions on Kewaunee River.

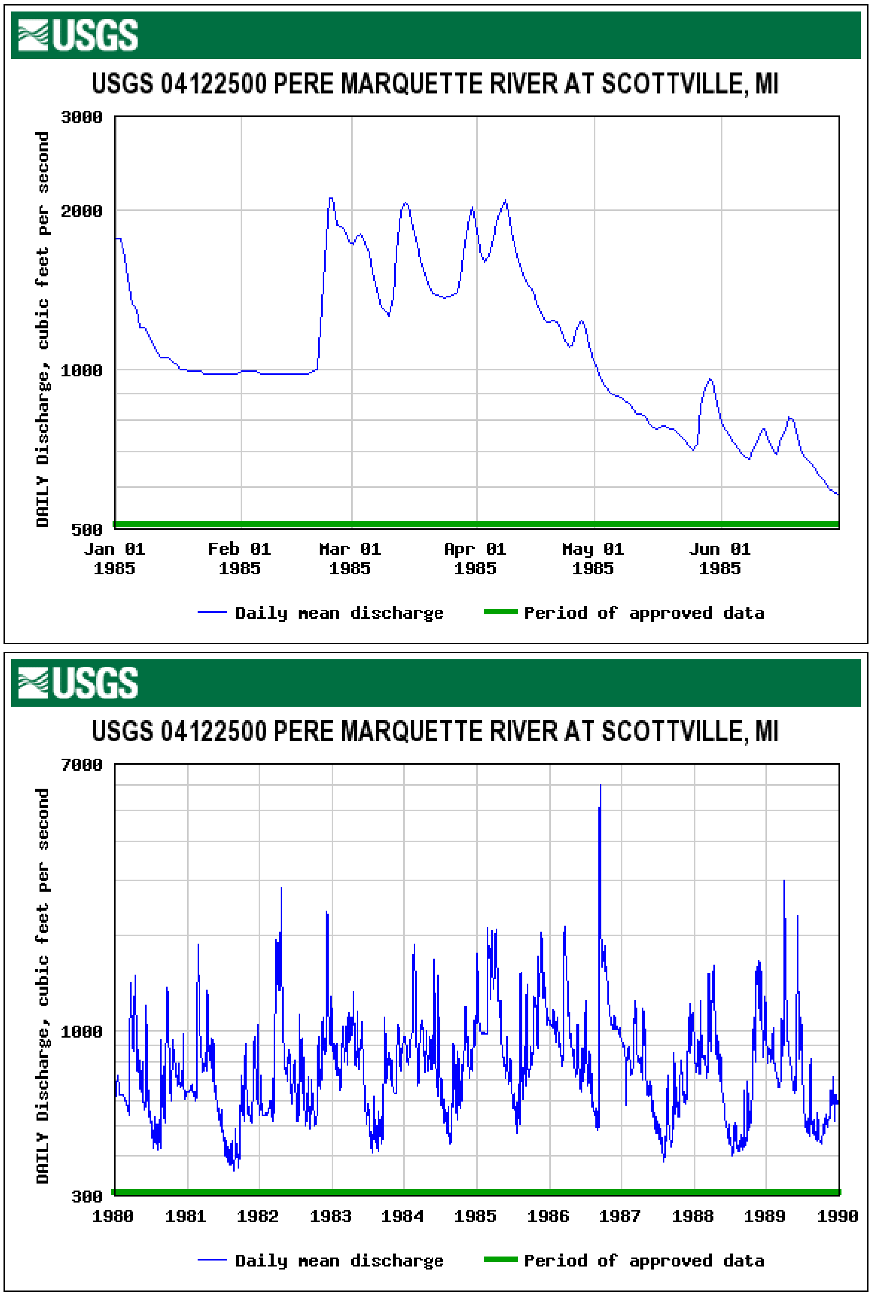


Figure B31. Local hydraulic conditions on Pere Marquette River.

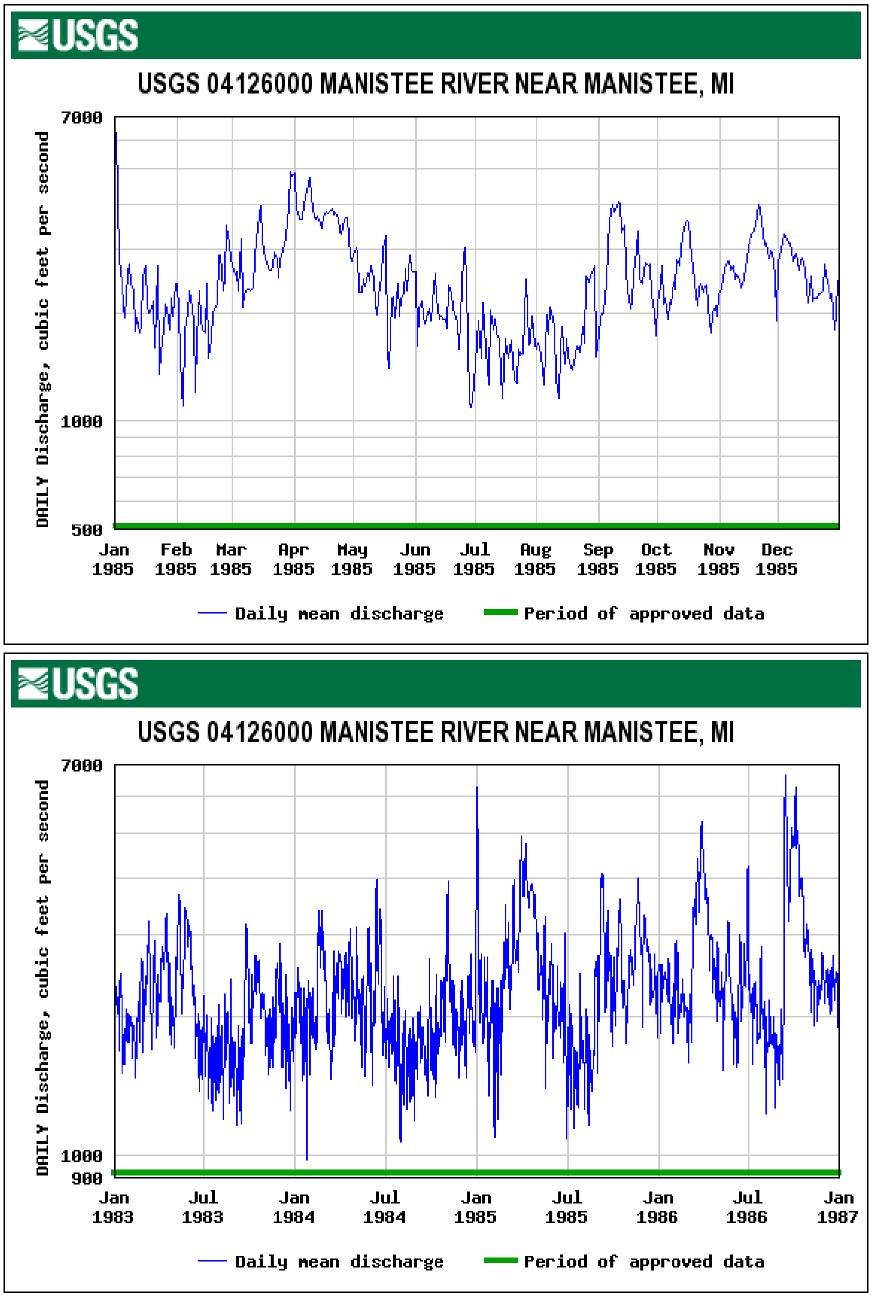


Figure B32. Local hydraulic conditions on Manistiee River.

Storm 6: Most significant event at Port Inland water level gage

Storm date: 11 January 1975

This storm produced the highest surge on record of 3.67 ft at Port Inland, MI. The storm did not register a top 20 surge at any other station.

Storm summary from NOAA National Weather Service storm data

Storm summary for Michigan

"Storm surge caused flooding on east and north shores of Lake Michigan, erosion on east shore, and ice jam at north end of Green Bay."

Storm summary for Wisconsin

AN EXTREMELY INTENSE LOW PRESSURE SYSTEM, THE CENTER
OF WHICH PASSED THROUGH WESTERN AND EXTREME NORTHWEST
WISCONSIN, CAUSED VERY STRONG WINDS THROUGHOUT THE
STATE. CONSIDERABLE DAMAGE WAS REPORTED STATEWIDE,
INCLUDING NUMEROUS POWER FAILURES FROM DOWNED POWER
LINES, LARGE TREES AND SIGNS BLOWN DOWN, ALONG WITH
DAMAGE TO VARIOUS STRUCTURES. WIND DAMAGE WAS MOST
EXTENSIVE OVER THE SOUTHEASTERN HALF OF WISCONSIN.
SUSTAINED WINDS WERE AVERAGING AROUND 50 MPH WITH
FREQUENT GUSTS INTO THE 60 TO 70 MPH RANGE. HIGHEST
MEASURED WINDS IN GUSTS WERE 77MPH REPORTED BY WISCONSIN
POWER AND LIGHT AT ELDORADO IN FOND DU LAC COUNTY. OTHER
REPORTED GUSTS WERE 69MPH AT WEATHER SERVICE OFFICE
GREEN BYA BAY AND 65 MPH AT MILWAUKEE WEATHER OFFICE.
IN COLUMBIA COUNTY FROM NEAR FOND DU LAC TOWARD MADISON
A 63 MILE SECTION OF TRANSMISSION LINE TOWERS WERE
TOPPLED BY HIGH WINDS. THE REPLACEMENT COSTS OF THESE
TOWERS WERE PUT AT AROUND 4 MILLION DOLLARS. OTHER SCETIONS
OF TRANSMISSION TOWERS WERE DOWN SOUTH OF MADISON. DESIGN
LIMITS FOR THESE TOWERS WERE SET TO WITHSTAND WINDS OF 100MPH.
Over the SOUTHEAST HALF OF THE STATE NUMEROUS REPORTS OF
MAINLY MINOR DAMAGE TO BUILDINGS WERE RECEIVED, WITH
PARTIALLY BLOWN OFF ROOFS, BLOWN DOWN BARNS, AND BROKEN
PLATE GLASS WINDOWS. A HUGE 110 FOOT CRANE WAS DESTROYED
NEAR GREEN BAY. IN PESHTIGO NORTH OF GREEN BAY A 200 BY 20
fOOT SECTION OF A WALL MADE OF 12 INCH THICK CONCRETE BLOCK
OF AN INDUSTRIAL BUILDING WAS DESTROYED. ONE DEATH OCCURRED
IN MANITOWOC AS A PIECE OF LUMBER DRIVEN BY THE WIND
HIT A MAN IN THE HEAD. TWO PEOPLE DIED OF EXPOSURE IN THE
MILWAUKEE AREA AS WINDS AND FALLING TEMPERATURES DEVELOPED
ON THE 11th.

Storm hydrographs

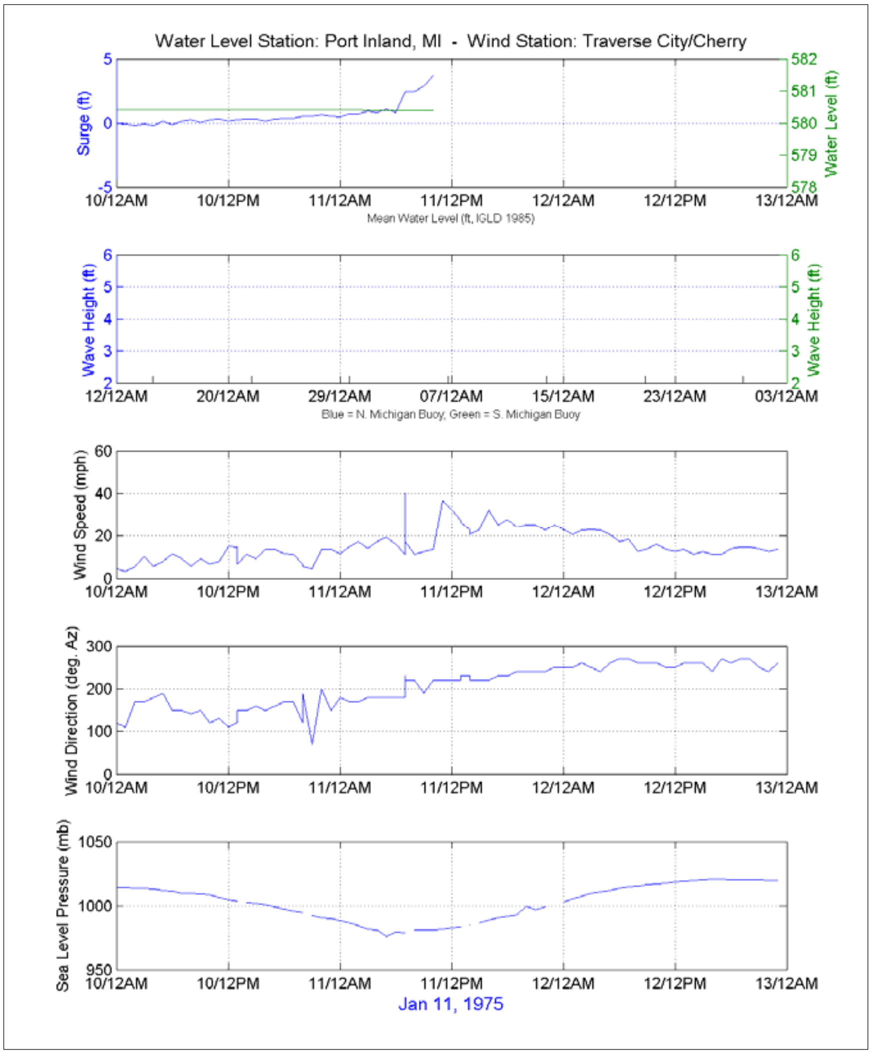


Figure B33. Partial surge hydrograph during storm at Port Inland and meteorological measurements from Traverse City.

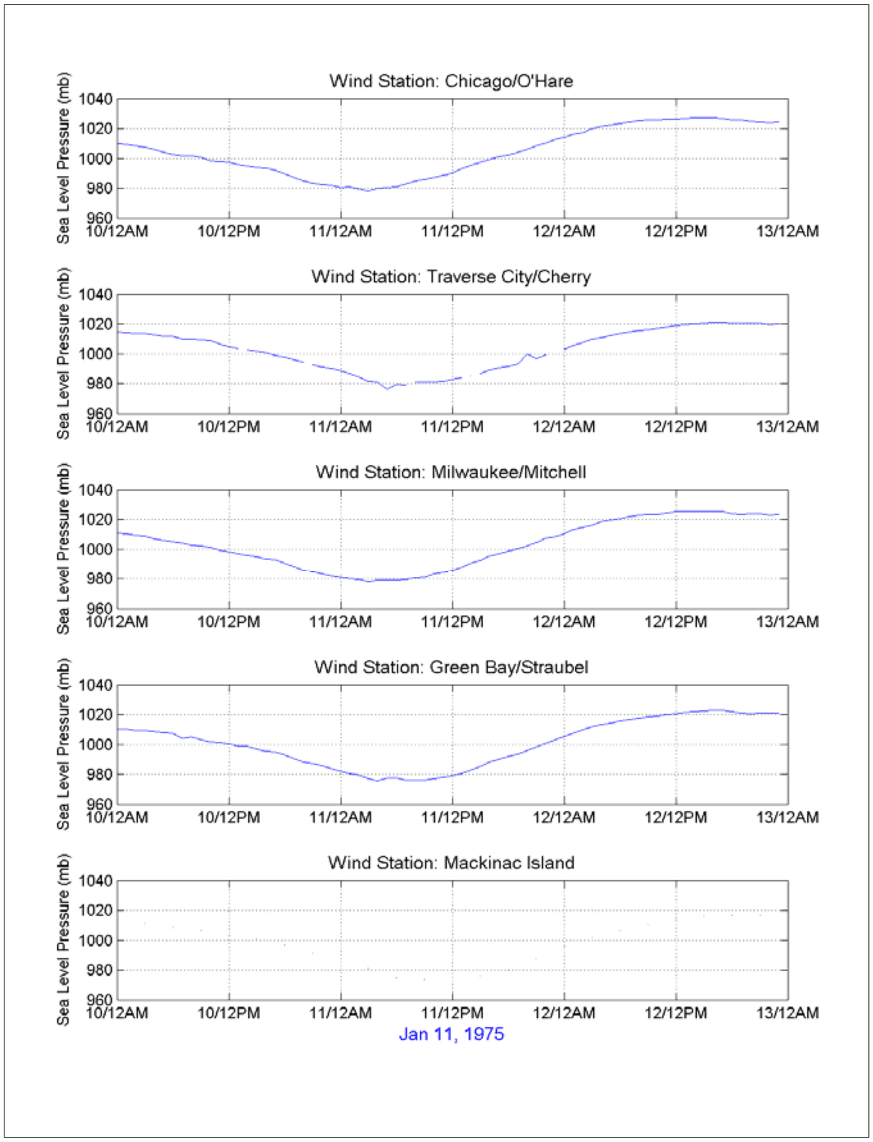


Figure B34. Atmospheric pressure measurements during storm.

Storm winds

Table B8. Winds during storm in knots.

Date	3-Hour Time Interval	Sault St. Marie, MI		Muskegon, MI		Green Bay, WI	
		Wind Spd	Wind Dir	Wind Spd	Wind Dir	Wind Spd	Wind Dir
Jan. 10, 1975	1	11	120	14	110	10	140
	4	14	130	11	110	12	110
	7	16	120	15	120	9	90
	10	20	110	16	100	10	50
	13	20	120	13	110	10	80
	16	18	120	13	130	10	60
	19	18	100	18	140	9	60
	22	17	110	23	140	15	150
Jan. 11, 1975	1	13	110	15	160	8	160
	4	15	140	32	220	30	210
	7	15	160	35	220	38	210
	10	18	200	37	230	35	210
	13	27	220	35	220	38	220
	16	20	220	26	230	33	240
	19	20	250	21	230	25	260
	22	19	240	25	230	23	220
Jan. 12, 1975	1	14	250	22	230	23	250
	4	11	270	19	250	23	240
	7	12	280	20	240	22	250
	10	20	280	16	240	24	270
	13	12	280	14	250	18	250
	16	11	240	15	250	15	260
	19	7	270	16	240	15	260
	22	9	240	14	260	12	270

Regional ice cover

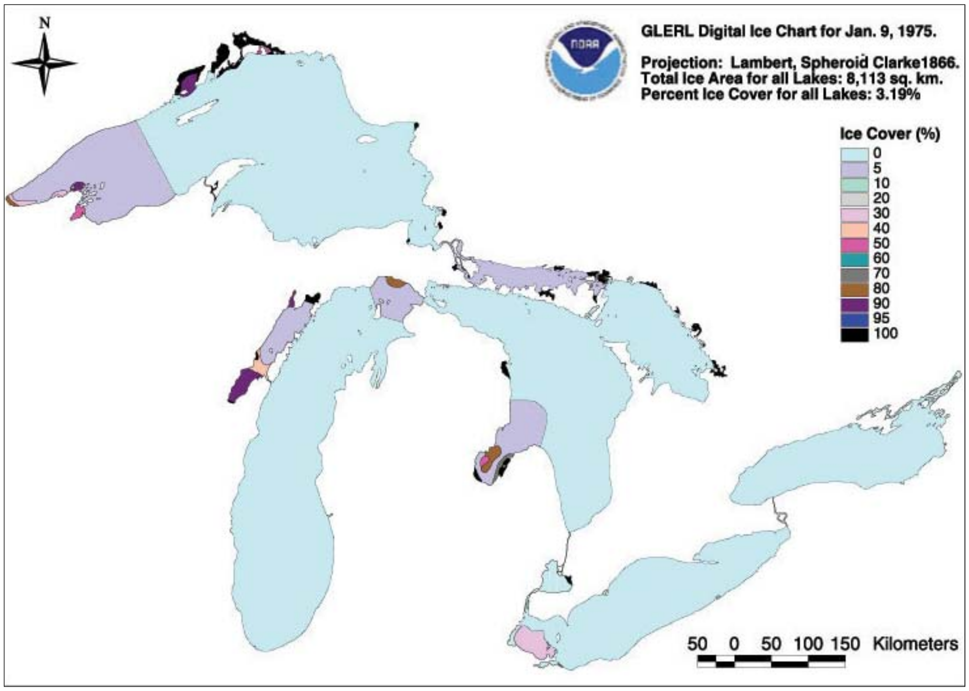
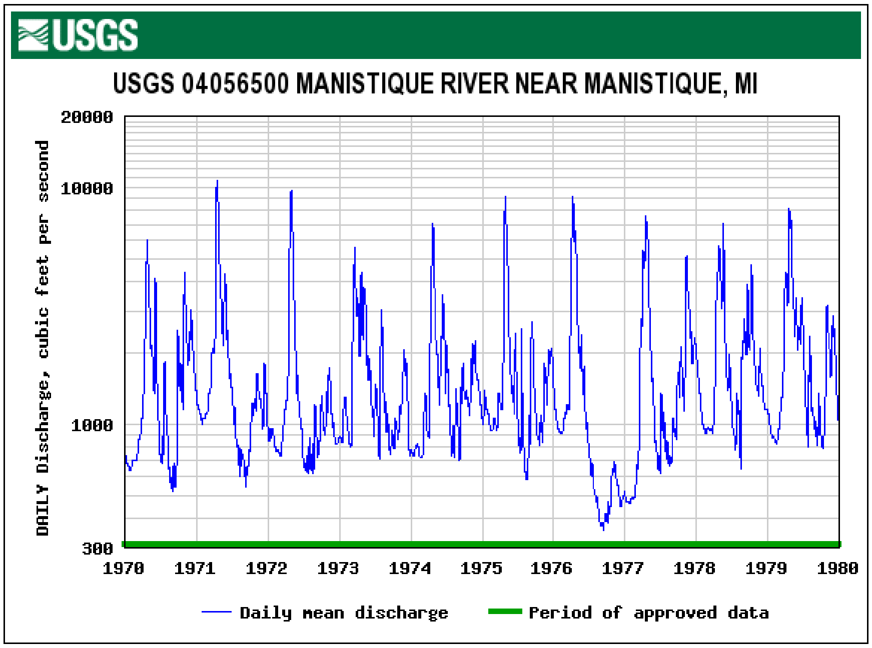


Figure B35. Ice cover on 9 Jan, 2 days before storm.

Local hydraulic conditions



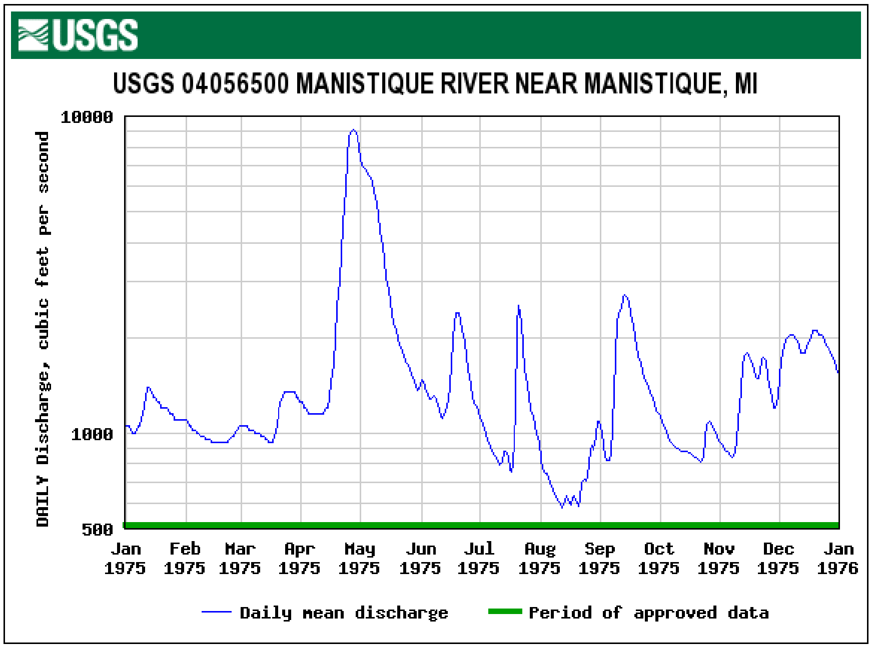


Figure B36. Local hydraulic conditions on Manistique River.

Storm 7: Significant event at two water level gages

Storm date: 24-25 December 1965

Table B9. Locations where storm produced top 20 surge levels.

Station	Surge (ft)	Station Rank
Green Bay, WI	3.76	2
Calumet, IL	3.31	2

Storm summary NOAA National Weather Service storm data

Storm summary for northern Illinois

Heavy rains totaled 3 to 5 inches over much of area from Chicago south to Bloomington. Local flooding caused extensive damage, especially in southern suburbs of Chicago. Unofficial measurements were as high as 6½". The change to sleet, freezing rain, and snow caused major power outages throughout the area with counties of McLean, La Salle, Bureau, Putnam, Kankakee, Will, McHenry, DuPage and Cook among the hardest hit. Although losses reached several millions of dollars, the wide variety of types and areal extent of damage precluded a total estimate. sleet, and snow

Storm summary for northern Indiana

Rain exceeding four inches in a few hours flooded 80 homes at Michigan City, some homes in Portage, and a factory at Auburn.

Storm summary for southeastern Wisconsin

Heavy wet snow whipped by high winds did extensive damage to utility wires and trees in southeastern Wisconsin. 40,000 homes without electricity for various lengths of times during Christmas season in Milwaukee and surrounding counties. About 10 inches of snow fell at Milwaukee and northerly winds gusted at 40-60 MPH.

Storm winds

Table B10. Winds during storm in knots.

Date	3-Hour Time Interval	Green Bay, WI		Milwaukee, WI		South Bend, IN	
		Wind Spd	Wind Dir	Wind Spd	Wind Dir	Wind Spd	Wind Dir
Dec. 23, 1965	1	4	90	6	20	8	210
	4	8	70	3	340	9	210
	7	10	80	4	200	10	190
	10	6	80	8	180	10	180
	13	8	160	11	200	14	200
	16	11	230	14	210	15	200
	19	8	260	12	230	13	210
	22	7	280	8	250	13	210
Dec. 24, 1965	1	7	290	3	300	14	210
	4	6	340	7	30	11	220
	7	8	20	11	30	15	190
	10	12	30	11	30	11	180
	13	11	30	16	30	6	30
	16	18	20	18	30	6	100
	19	12	30	20	30	8	60
	22	16	20	22	30	16	30
Dec. 25, 1965	1	18	20	31	30	18	30
	4	20	20	27	30	19	30
	7	15	10	19	350	21	360
	10	15	20	24	360	18	350
	13	17	30	20	360	18	360
	16	14	30	22	30	17	10
	19	7	360	15	360	12	20
	22	8	20	10	20	12	10

Local hydraulic conditions

At both Green Bay and Chicago, stream discharge rates are well above normal, indicating that it is possible that high surge readings in part were driven by localized flooding events.

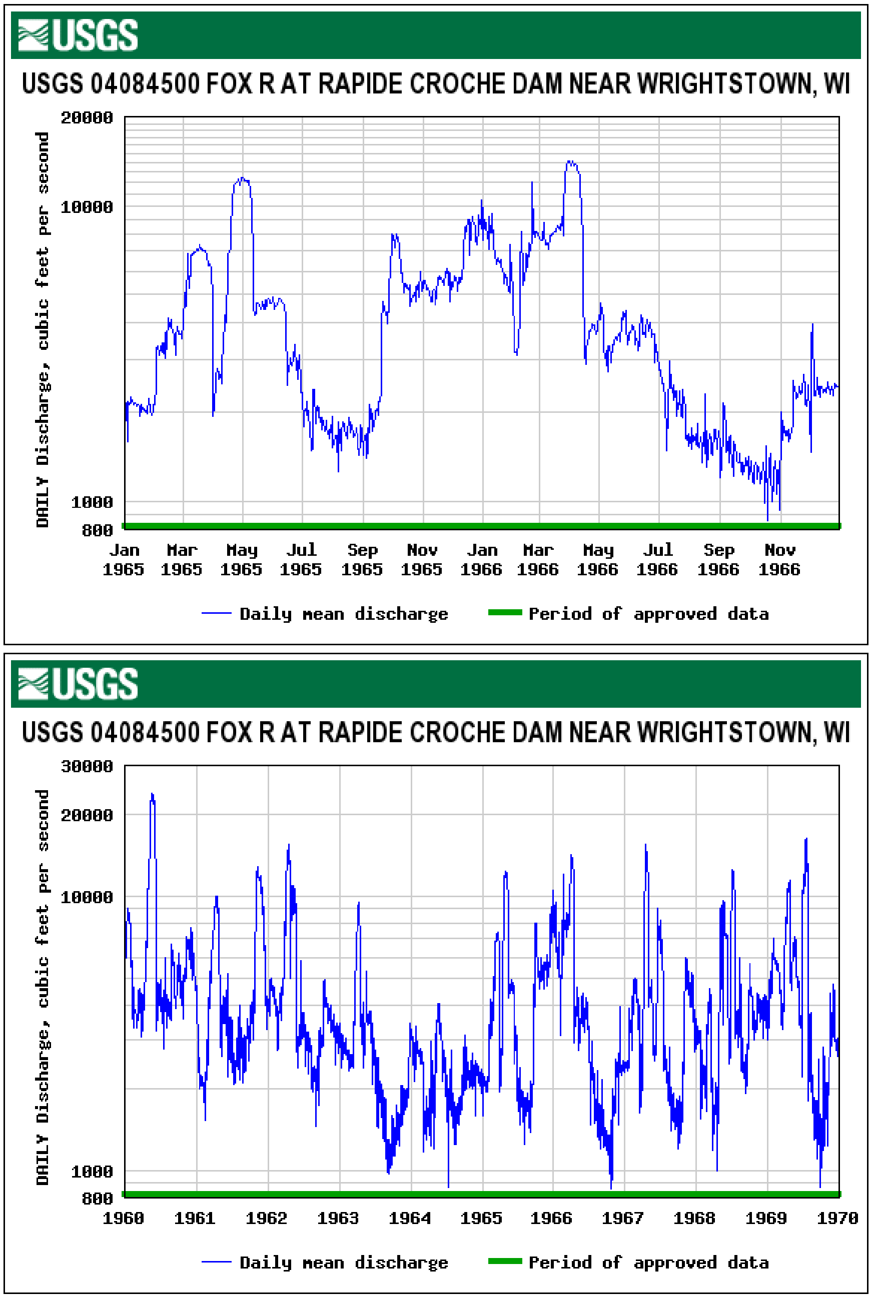


Figure B37. Local hydraulic conditions at Rapide Croche Dam

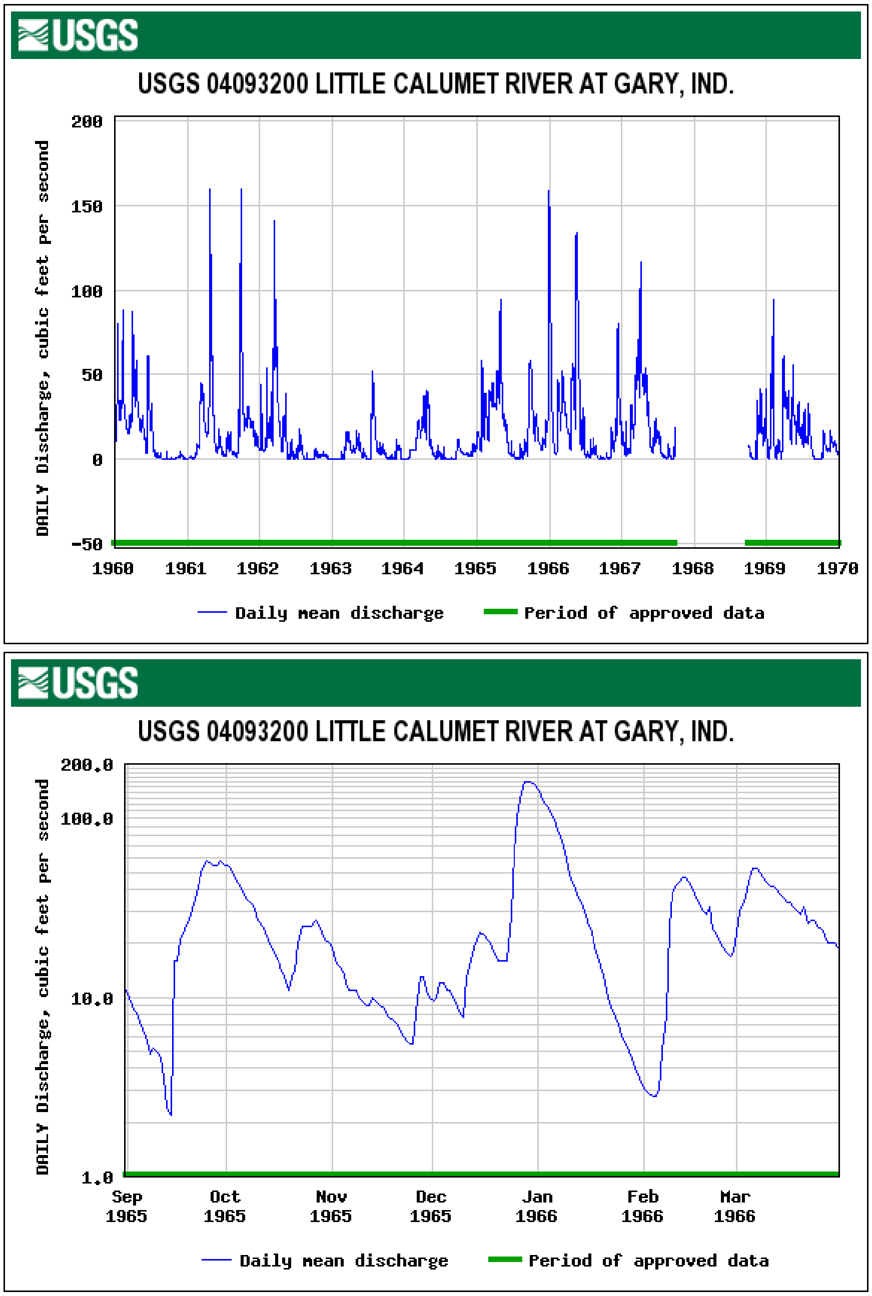


Figure B38. Local hydraulic conditions on Little Calumet

Storm 8: Significant event at Calumet water level gage

Storm date: 21-22 October 1929

Produced top 20 surge at Calumet Harbor, IL

Storm summary from NOAA National Weather Service storm data

with 2.12 inches within 24 hours on the 28-29th. October was somewhat cooler and wetter than usual. A severe storm occurred on the 21-22d. Streets and parks adjacent to the Lake were flooded and strewn with debris. Boats were beached in the harbors, and shore line improvements were badly wrecked. November was colder and drier than normal.

Max. winds on the 22^{nd} of 34 knots, with a prevailing direction of NW.

A severe windstorm on Lake Michigan on the 22-23d with attendant high water caused damage along the Wisconsin shore of Lake Michigan estimated at more than $1,000,000. This

Appendix C: Storm Summaries for Lake St. Clair

Storm 1: Most significant surge event at Lake St. Clair

Storm date: December 3 – 4, 1990

This event was also the most significant event for Lake Michigan.

Table C1. Locations where storm produced top 20 surge levels.

Station	Surge (ft)	Station Rank
Fort Wayne, MI	2.25	1
Windmill Pt., MI	1.38	1
St. Clair Shores, MI	0.97	2

Storm track

Records indicate the storm was cyclonic and was centered over northeast Oklahoma on Dec. 3rd, over southern Lake Michigan on Dec. 4th, and over southwestern Quebec on Dec. 5th. See Figure B1.1

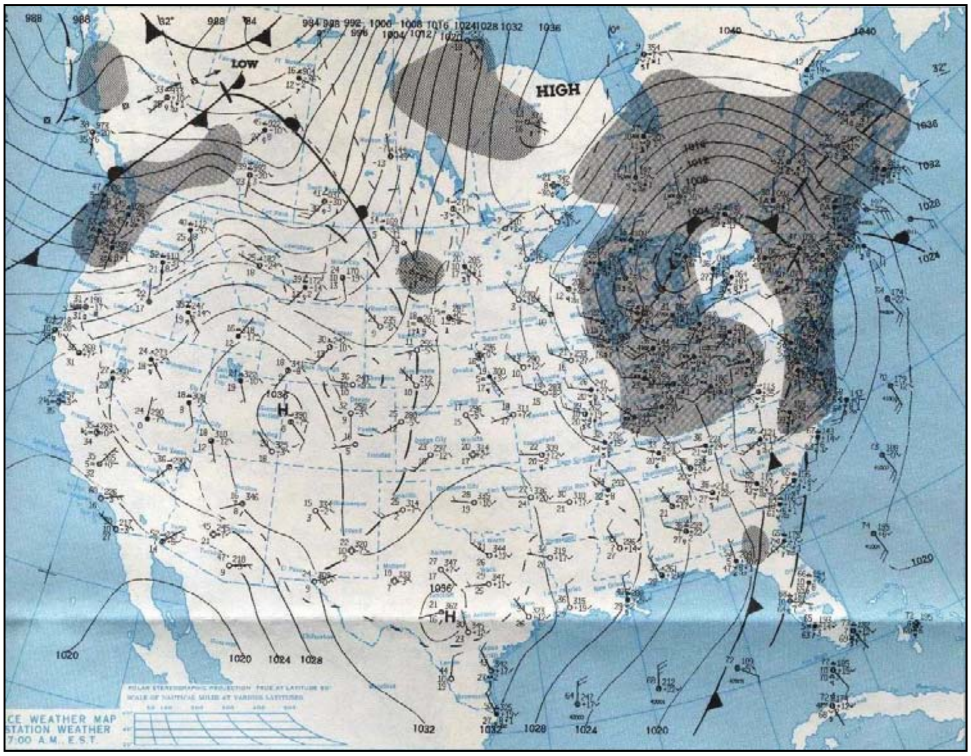


Figure C1. Storm weather map of Dec. 1990, showing Dec. 3rd-4th storm.

Storm summary from NOAA National Weather Service storm data

The first December snowfall in Michigan was the most intense storm of the month and season thus far. A fairly strong low-pressure system moved northeast, across Lake Michigan, late in the afternoon on Monday, December 3rd. From there, the storm moved slowly northeast, crossing northern Lake Huron during Tuesday morning, but not moving east of Lake Huron until late Tuesday afternoon. As a result, heavy snow fell in 43 of Michigan's 83 counties. Light snow began falling over southern-lower Michigan before sunrise on Monday. Snow began falling over the upper Peninsula by noon. Heavy snow with gale-force winds began blowing across most of northern-lower and upper Michigan by early afternoon. The snow ended as flurries, in most areas, by around 1500 EST on Tuesday, December 4th; however, the northwestern winds blowing across the widest part of Lake Michigan during Tuesday afternoon, caused a lake-effect snow band about 20-miles wide, remain nearly stationary from near Holland (on the Lake Michigan shoreline in northwestern Ottawa County), southeast across Battle Creek, to near Coldwater, in central Branch County. This snowbank developed early Tuesday morning and finally dissipated around 1900 EST that evening. Snowfalls in the snow band ranged from 8 to 14 inches; 11 inches on average. Over the main storm snow area, 6 to 10 inches were common across northern-lower Michigan, with two areas of 12 inches. One snow band occurred over

northeastern-lower, and the second over the Leelanau Peninsula, north of Traverse City. The upper peninsula had the most snowfall; 6 to 15 inches in most areas, with the greatest reported snowfall from Champion, (in western Marquette County) where 20 inches were reported. Due to high winds and heavy snow, considerable drifting occurred. This caused many school closings in northern-lower and upper Michigan on Tuesday. There were many reports of winds between 30 and 40 mph with frequent gusts near 50 mph. Ontonagon reported the highest gust of 64 mph. All airports in the area were closed and about 80,000 customers lost power across Michigan, during this blizzard. Four-thousand calls were made to the AAA Motor Club for road assistance; over 100 auto accidents were reported. One accident was fatal to a 56-year-old man, near Traverse City, when he crashed Tuesday morning around 1045 EST. The high winds caused some building damage near the Lake Huron shoreline. This included bricks blown off a building wall into the plate glass of the adjoining building. After all was done late on Tuesday evening, this storm will remain as one of the more memorable storms of this season.

Storm hydrographs

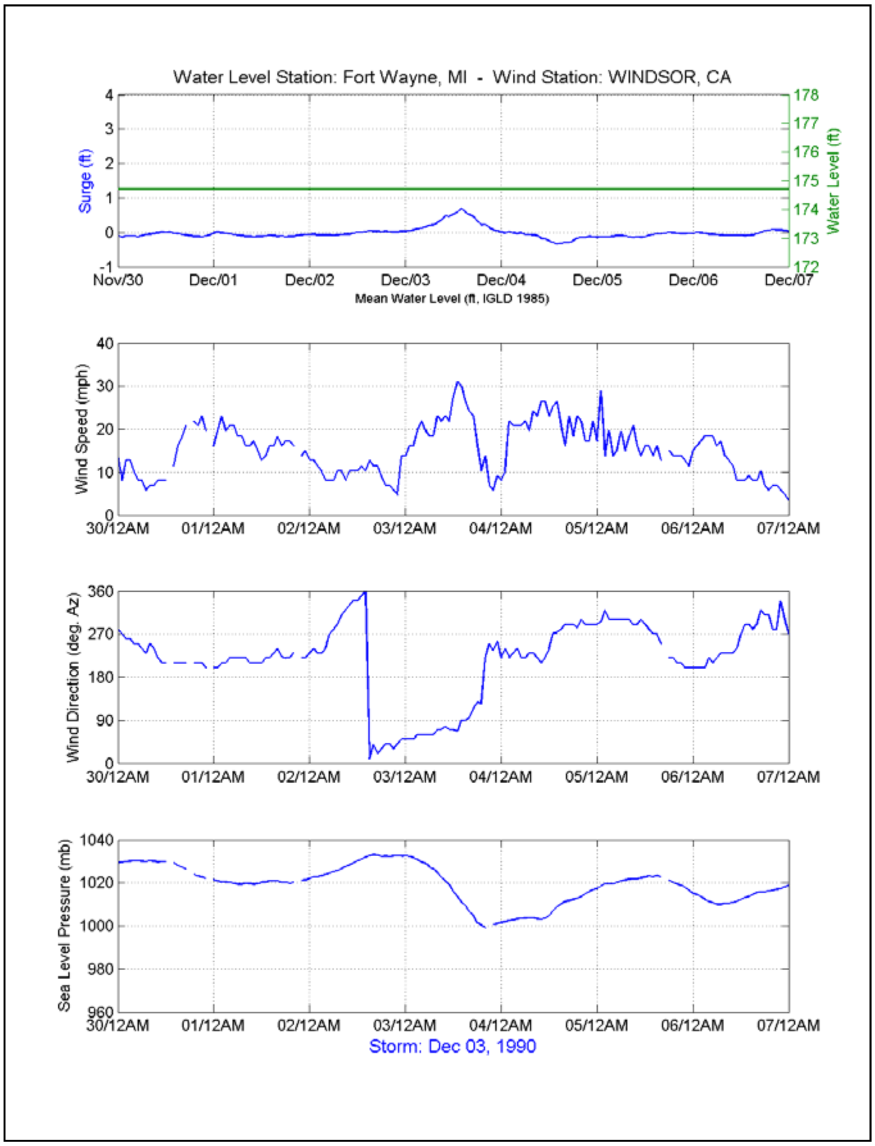


Figure C2. Surge at Fort Wayne and meteorological measurements at Windsor.

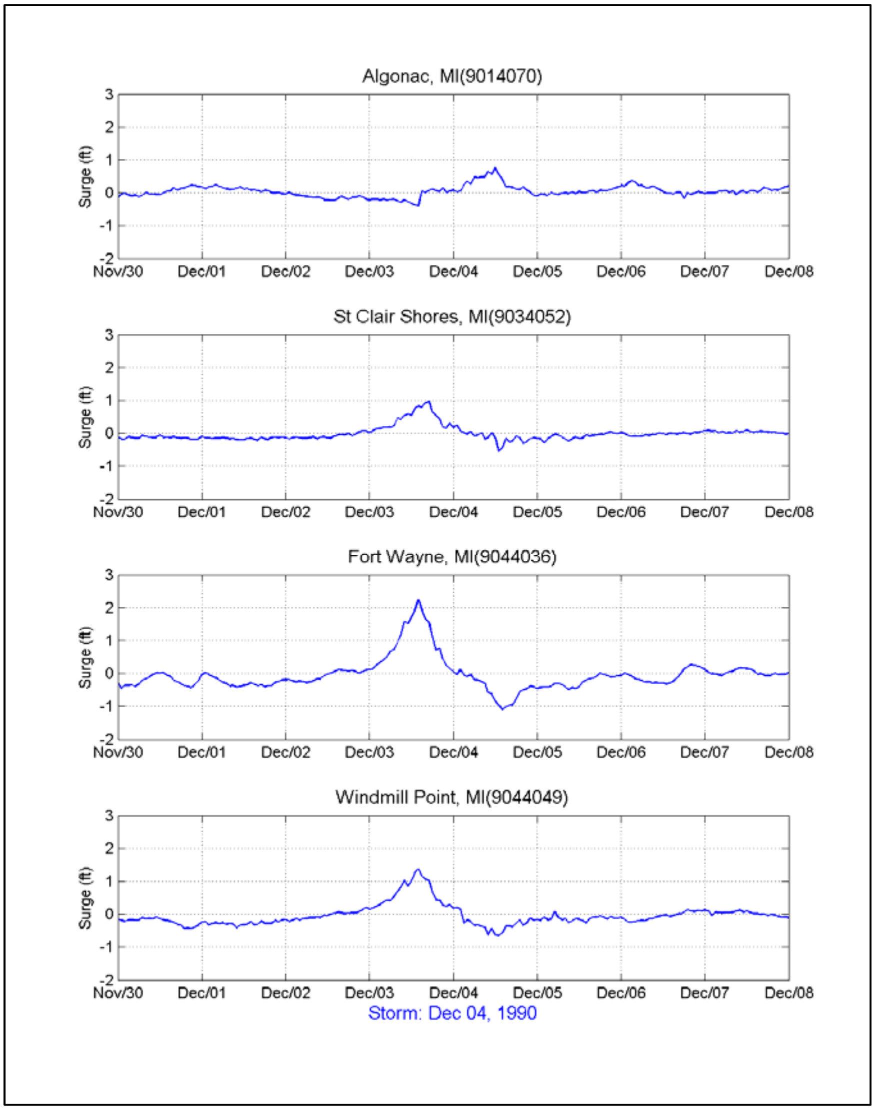


Figure C3. Surge measurements at each gage station.

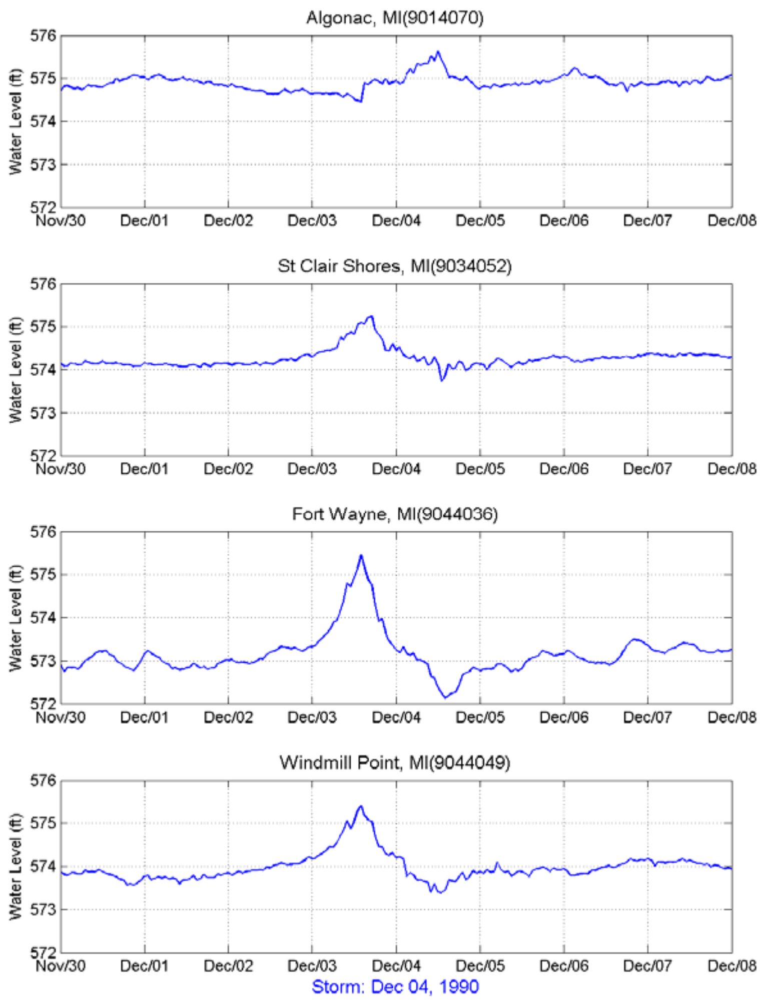


Figure C4. Water level measurements at each gage station during the event.

Storm winds

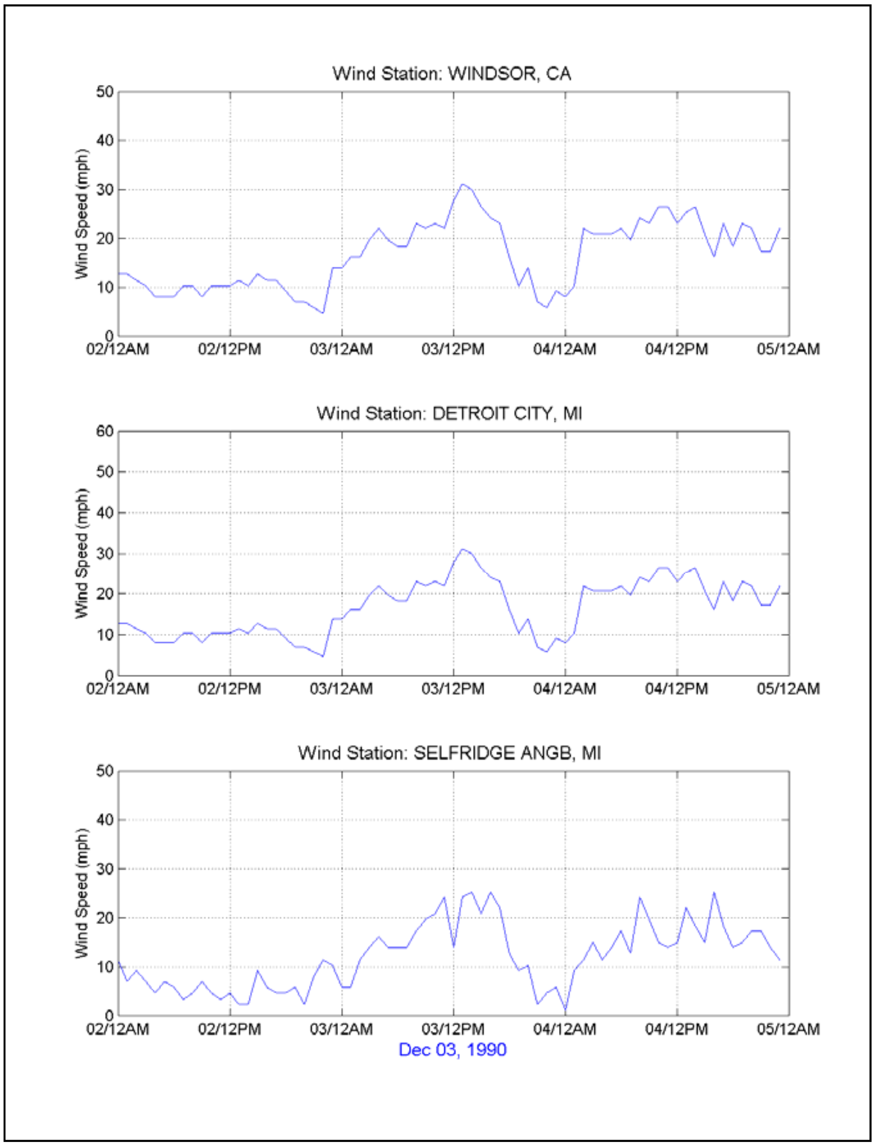


Figure C5. Wind measurements during storm.

Barometric pressures

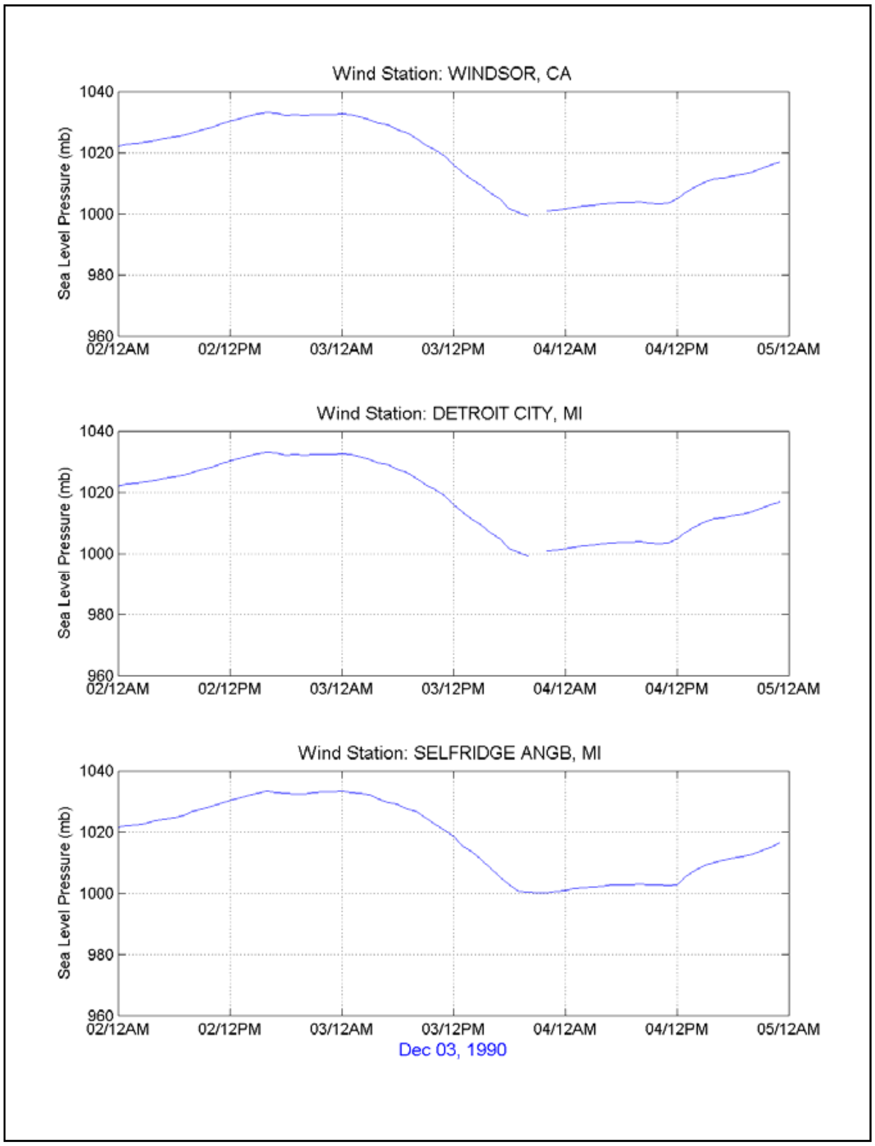


Figure C6. Atmospheric pressure measurements during storm.

Regional ice cover

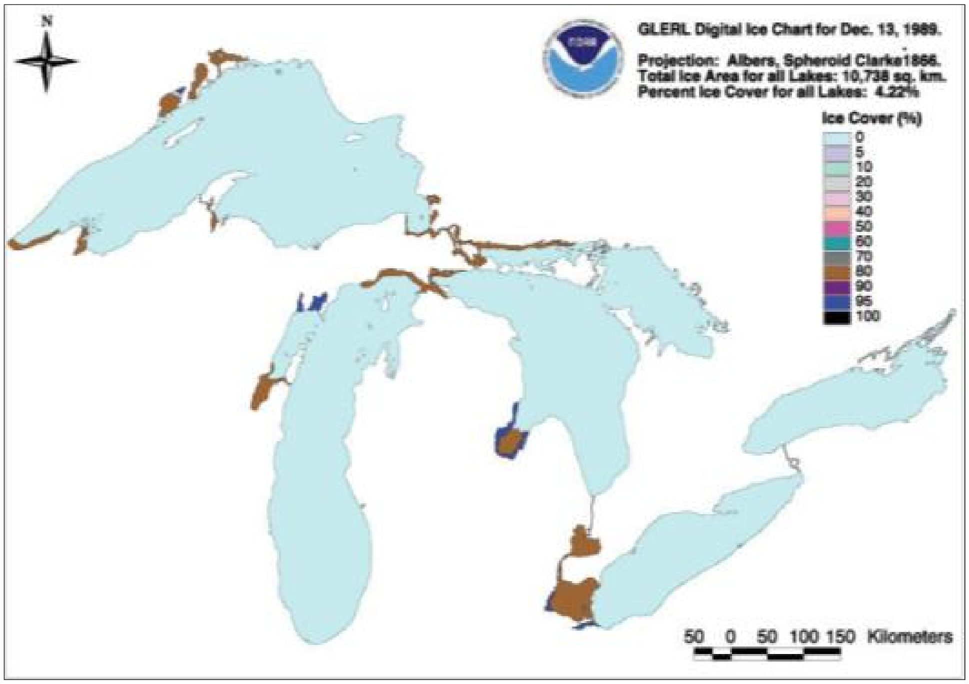


Figure C7. Regional ice cover on 13 Dec, ten days after storm.

Storm 2: Most significant event at St. Clair Shores water level gage

Storm date: December 15, 1987

Table C2. Locations where storm produced top 20 surge levels.

Station	Surge (ft)	Station Rank
St. Clair Shores, MI	0.95	3
Fort Wayne, MI	1.64	6
Windmill Pt., MI	1.01	13

Note: There are no data available at Algonac for this event.

Storm track

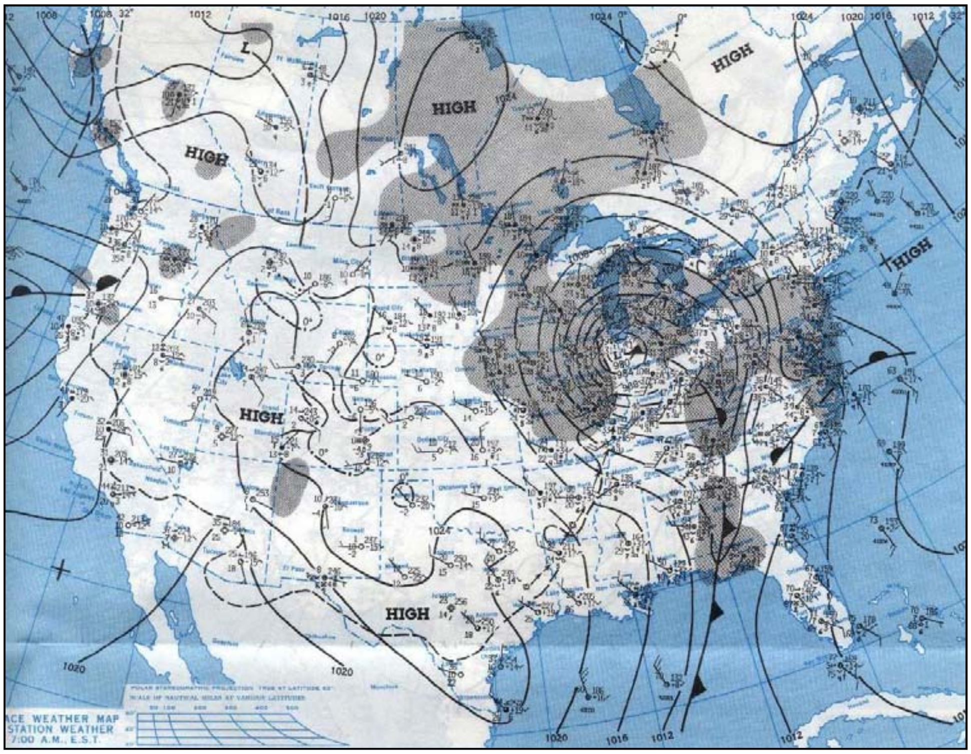


Figure C8. Weather map during event.

Storm Summary

The Blizzard on December 14-15, 1987 covered the south half of Wisconsin with 10 - 17 inches of snow. Wind gusts to 73 mph along the Lake Michigan shore in Milwaukee, generated 10 to 15 foot waves. The large waves repeatedly pushed a Greek cargo ship into a dock in the harbor, causing $100,000 in damage. Washington county reported 16 inches of snow. Milwaukee and Madison had 13 inches of snow. The winter storm dropped 8 - 12 inches of snow from Grand Haven to Ludington. Muskegon set a daily record of 12.1 inches of snow.

Storm hydrographs

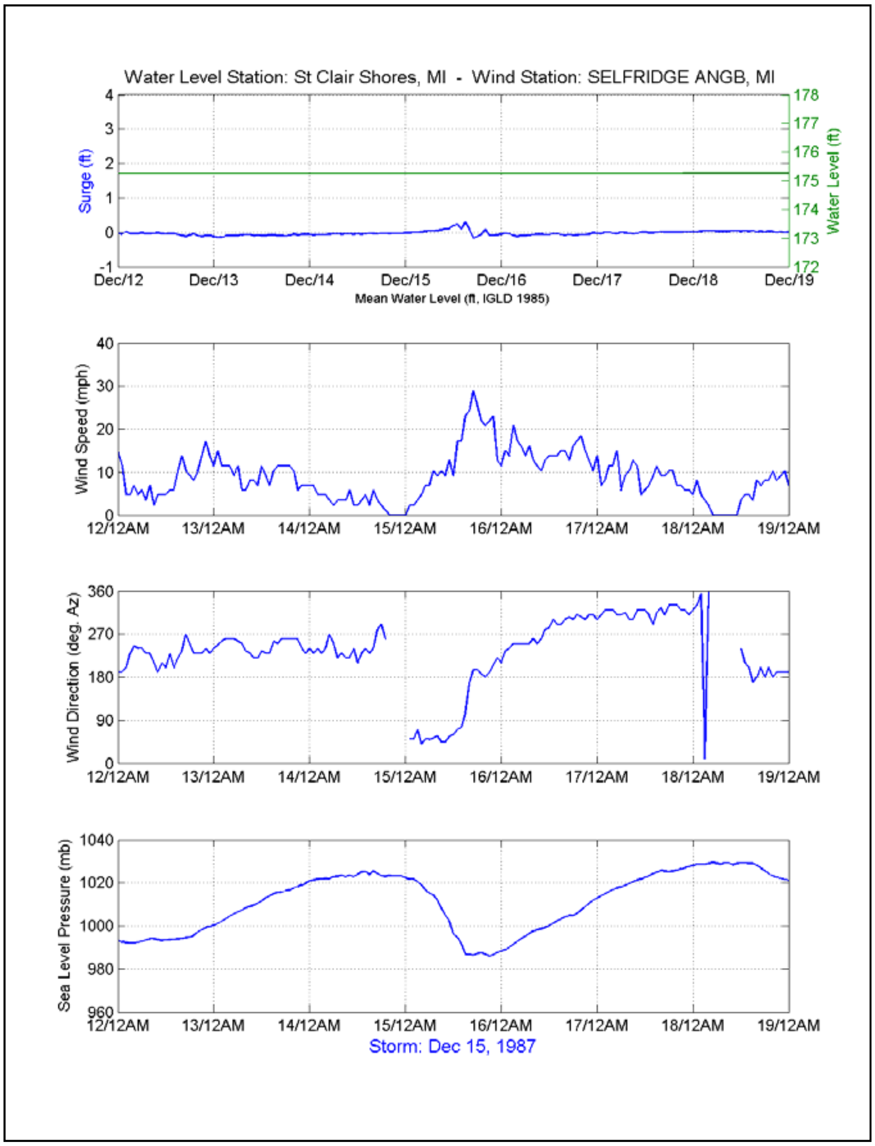


Figure C9. Surge at St. Clair Shores and meteorological measurements at Selfridge.

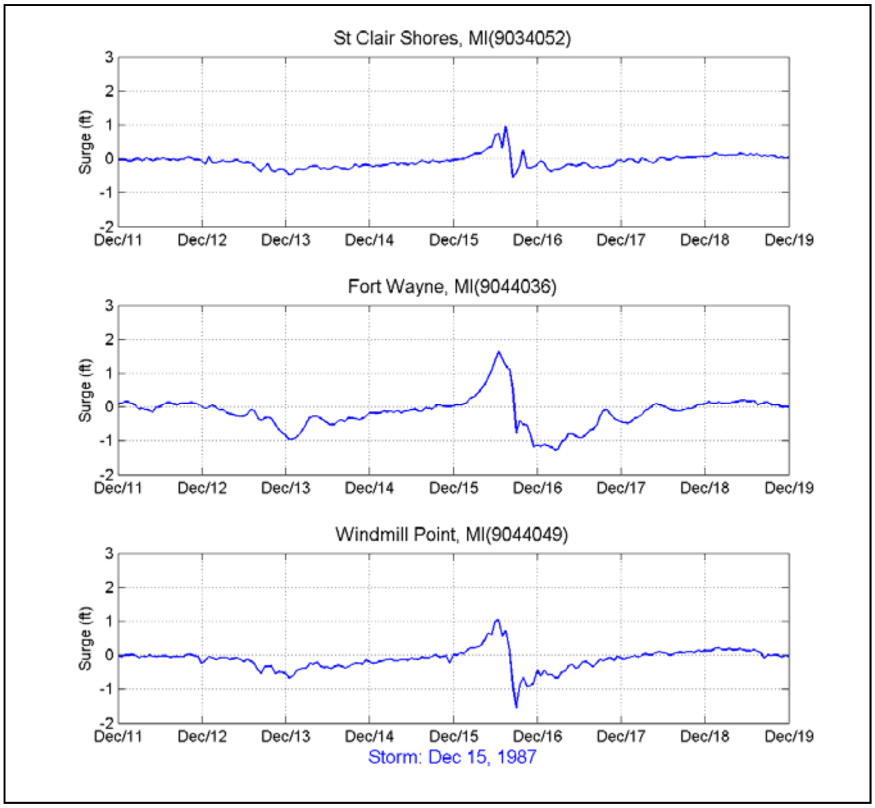


Figure C10. Surge measurements at each gage station during the event.

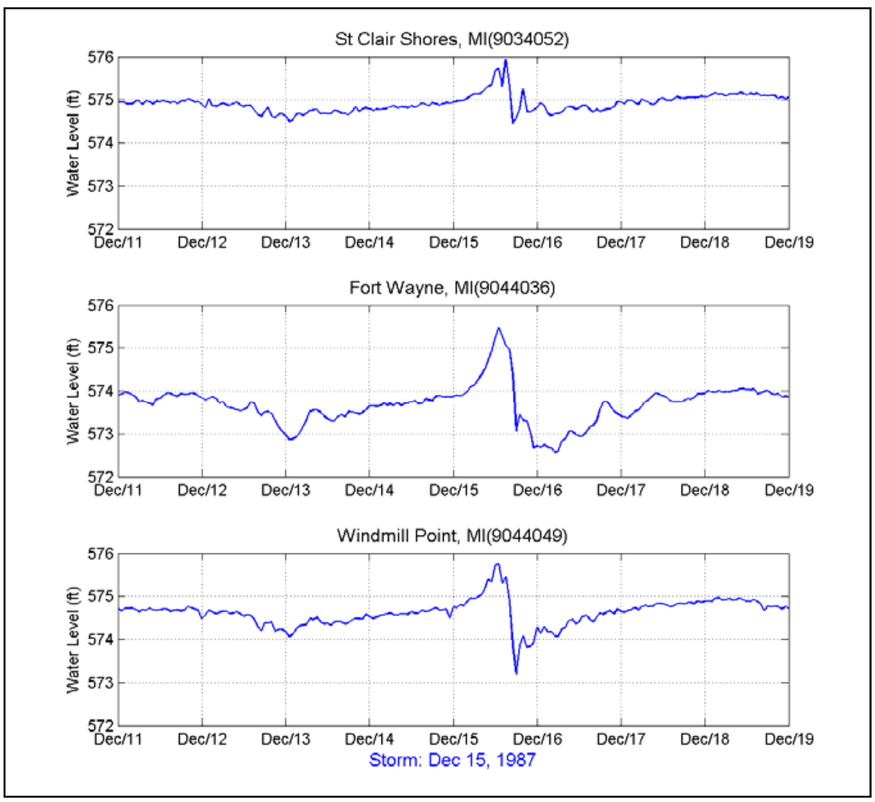


Figure C11. Water level measurements at each gage station during the event.

Storm winds

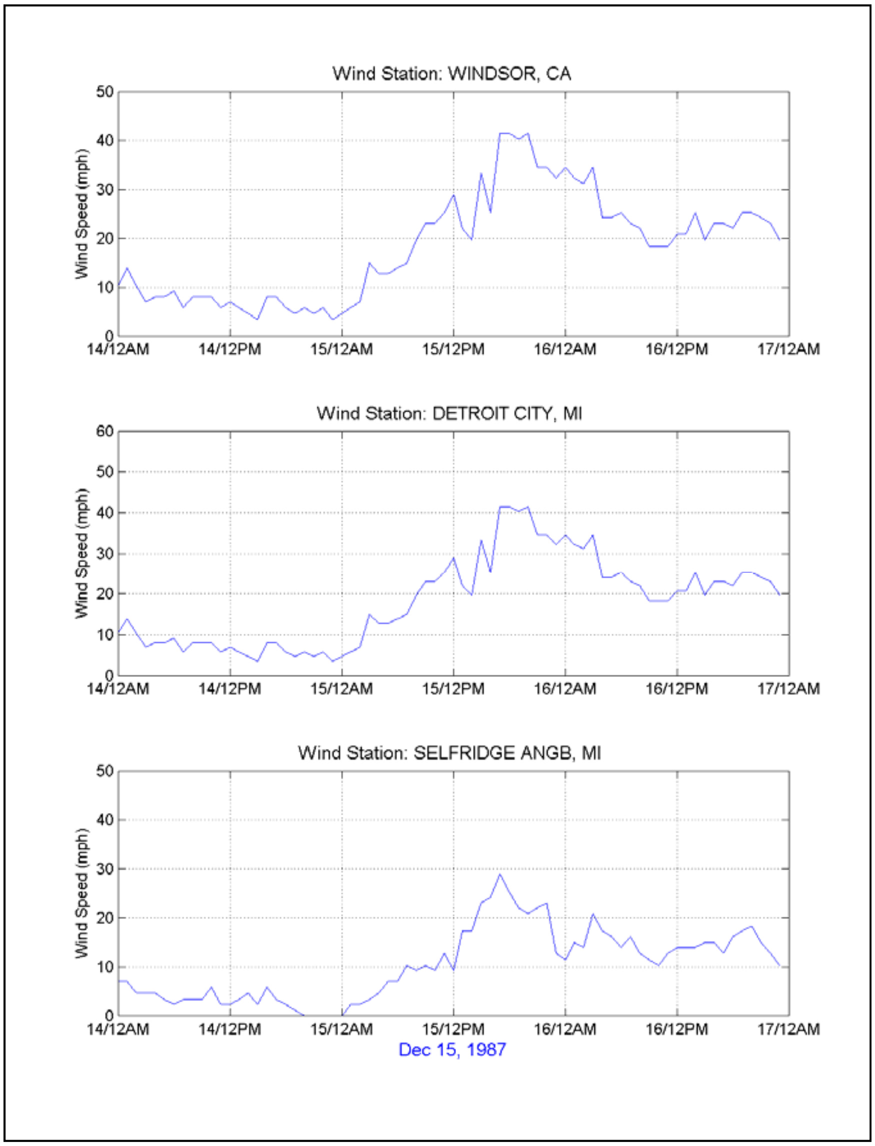


Figure C12. Wind measurements during storm.

Barometric pressures

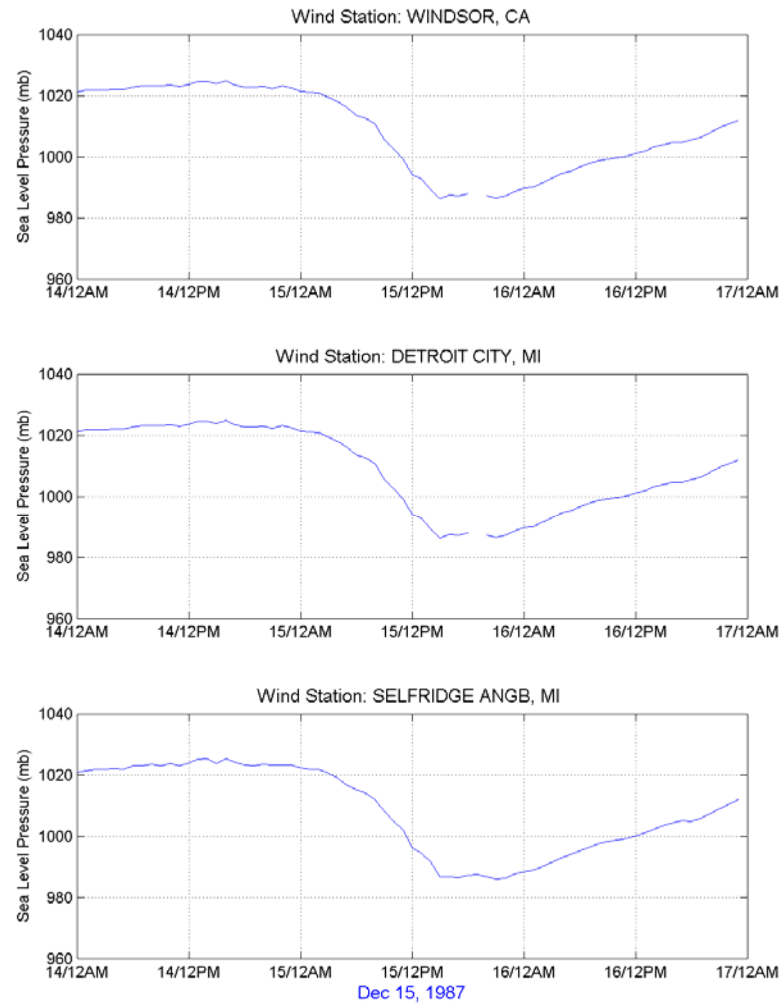


Figure C13. Atmospheric pressure measurements during storm.

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14. ABSTRACT

The Great Lakes are subject to coastal flooding as a result of severe storms. Strong winds blowing across the surface of the lakes produce high waves and surge. Variations in lake levels due to decadal scale variations in precipitation and anthropogenic activities affect the risk of flooding. In this report, historical storm climatology on Lakes Michigan and St Clair, and the resulting measured waves and water levels, are analyzed in detail. The physical processes that produce coastal flooding are investigated. The detailed history of water level and wave time series and associated probabilities are calculated, with long term, seasonal, and event time scales analyzed separately. Various parametric correlations between time scales and between spatial locations are quantified. A flood map methodology is proposed that improves the accuracy of base flood elevation prediction and improves the uncertainty prediction. The methodology takes full advantage of the latest storm wave and water level hydrodynamic modeling capabilities, as well as long term meteorological, ice, wave, and water level measurements.

15. SUBJECT TERMS

	Extratropical storms	Statistical analysis
Base flood elevation	Great Lakes	Water levels
Coastal flood	Mapping guidelines	Waves

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